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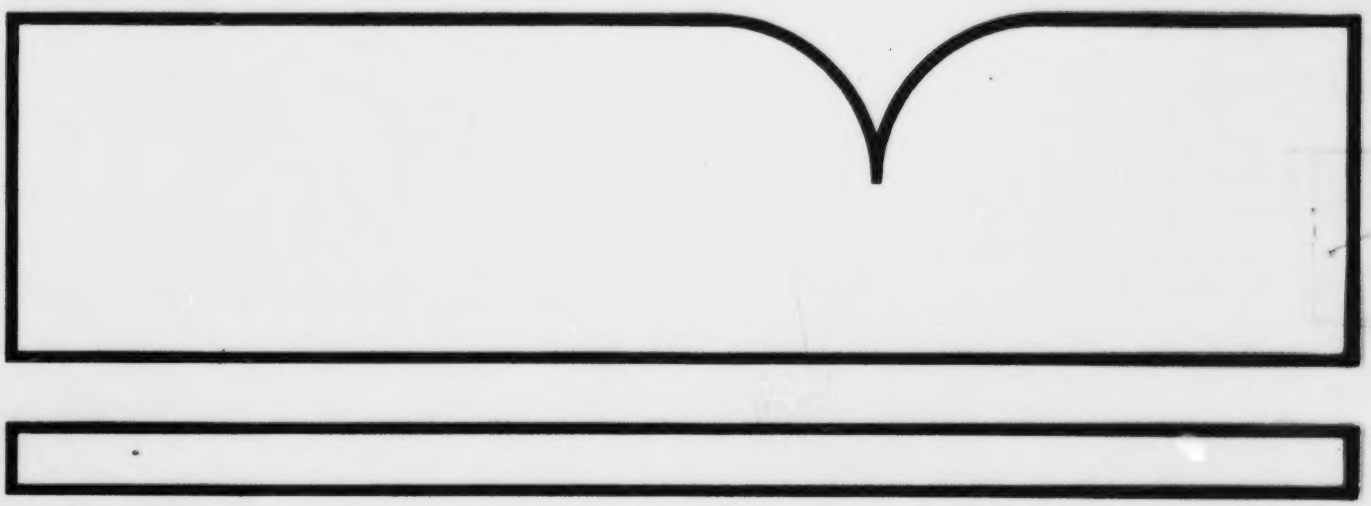
Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site K

KVB, Inc.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

May 80



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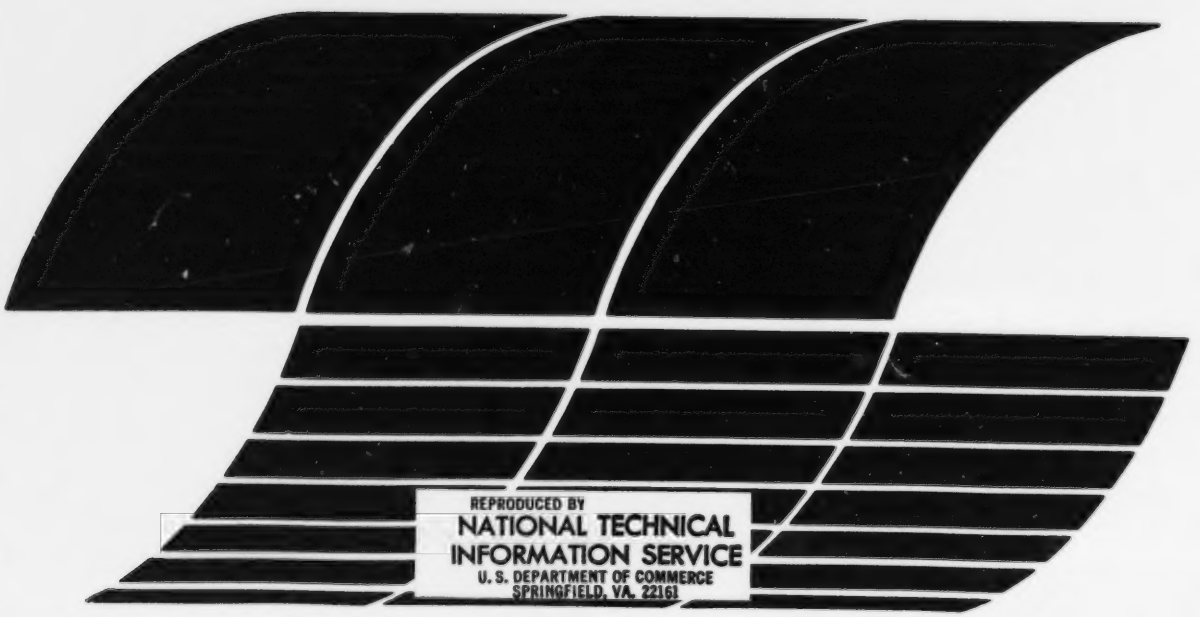
Interagency Energy/Environment R&D Program Report



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May 1980

Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement — Site K

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K. Luuri	Riley Stoker
D. McCoy	E. Keeler Company
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1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire air admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the last of eleven boilers tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The data supplement has the same EPA report number as this report except that it

is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a Final Technical Report will combine and correlate the test results from all sites tested. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the National Technical Information Service (NTIS) or through the EPA's Technical Library.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interests of the host boiler facilities, each test site in this program has been given a letter designation. As the eleventh site tested, this is the Final Technical Report for Test Site K under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A coal fired overfeed stoker with traveling grate was extensively tested for emissions and efficiency between September 15 and November 12, 1979. This section summarizes the results of these tests and provides references to supporting material found in the main text of this report.

UNIT TESTED: Described in Section 3.0, page 11.

- Riley Boiler

  Built 1977
  Type VO
  50,000 lb/hr rated capacity
  125 psig operating pressure
  Saturated steam
  Economizer

- Riley Stoker

  Overfeed stoker
  Traveling grate
  One row overfire air jets on front wall

COALS TESTED: Individual coal analysis listed in Tables 5-9, 5-10, 5-11 and 5-12. Commentary in Section 3.4, page 13, and Section 5.3, page 61.

- Washed Alabama Brilliant Coal

  13,237 Btu/lb
  4.14% Ash
  1.11% Sulfur
  6.49% Moisture
  2100° F Initial ash deformation temperature

- Unwashed Alabama Brilliant Coal

  12,280 Btu/lb
  10.24% Ash
  1.01% Sulfur
  6.19% Moisture
  2110°F Initial ash deformation temperature

- Washed and Crushed Alabama Brilliant Coal

  12,994 Btu/lb
  4.68% Ash
  1.31% Sulfur
  7.35% Moisutre
  2190°F Initial ash deformation temperature

OVERFIRE AIR TEST RESULTS: Normal operating practice on this boiler was to maintain overfire air pressure at 2.5" H_2O for all boiler loads. Three tests were conducted at overfire air pressures of 5.0" H_2O and one at 7.5" H_2O with the following results. (Section 5.1, page 35)

- Particulate Loading

  Uncontrolled and controlled particulate loadings dropped an average 20% when overfire air pressure was increased. A portion of this drop is attributed to more complete carbon burnout. (Section 5.1.1, page 35)

- Nitric Oxide

  Nitric oxide emissions were not influenced by the variable overfire air. (Section 5.1.2, page 38)

- Carbon Monoxide

  Carbon monoxide emissions were reduced by an average of 60% when overfire air was increased. (Section 5.1.3, page 39)

- Boiler Efficiency

  Boiler efficiency was not significantly altered by changes in overfire air pressure. (Section 5.1.4, page 39)

BOILER EMISSION PROFILES: Boiler emissions and efficiency were determined at of 50%, 75% and 100% of the units design capacity. At each load, excess oxygen varied within the range of ±1.4%. Data magnitude and trends were as follows. (Section 5.2, page 40)

- Excess Oxygen Operating Levels

  Excess oxygen decreased sharply as load increased. At full load, excess oxygen ranged from 6.0 to 8.8% O_2. Excess oxygen ranged from 9.8 - 11.6% at 75% capacity, and 10.8 - 13.6% at 50% capacity. (Section 5.2.1, page 40)

- Particulate Loading

  Uncontrolled particulate mass loading increased with increasing load, while controlled particulate mass loading decreased with increasing load. At full load, the washed coal averaged 0.78 $lb/10^6$Btu uncontrolled particulate mass loading, and 0.14 $lb/10^6$ Btu controlled. (Section 5.2.2, page 42)

- Nitric Oxide

  Nitric oxide was relatively invariant with load under normal operating conditions, and averaged 0.32 $lb/10^6$Btu. At full load, nitric oxide increased at the rate of 0.033 $lb/10^6$Btu for each 1% O_2 increase. (Section 5.2.3, page 45)

- Carbon Monoxide

  Carbon monoxide varied within the general range of 100 to 500 ppm. No correlation with load was observed. (Section 5.2.4, page 50)

- Combustibles in the Ash

  Combustibles averaged 32% in the uncontrolled flyash, 29% in the dust collector hopper ash and 42% in the bottom ash. Bottom ash combustible levels were unusually high. No correlation with load was observed. (Section 5.2.5, page 54)

- Boiler Efficiency

  Boiler efficiency increased with increasing load. At full load it averaged 78.4%. If bottom ash combustibles were a more normal 20% rather than the measured 42%, full load boiler efficiency would be 80.3%. (Section 5.2.6, page 54)

COAL PROPERTIES: The washed coal was the primary fuel at this facility. The unwashed coal was distinguished by its high ash content, and the crushed coal by its high fines. The effect of these coal properties on emissions and efficiency were as follows. (Section 5.3, page 61)

- Excess Oxygen Operating Conditions

  The unwashed coal used about 1% more O_2 than the washed coal, and the crushed coal used about 1% less O_2. (Figure 5-2, page 41)

- Particulate Loading

  Crushed coal produced 58% more uncontrolled particulates than the washed coal at full load. Unwashed coal produced 180% more uncontrolled particulates than the washed coal. Controlled particulates did not correlate as strongly with coal properties. (Figures 5-3 and 5-4, pages 43 and 44)

- Nitric Oxide

  No correlation with coal properties was observed. (Figure 5-7, page 49)

- Carbon Monoxide

  No correlation with coal properties was observed. (Figure 5-9, page 52)

- Sulfur Dioxide

  Sulfur content was not a variable. A sulfur balance attempt was not successful. (Table 5-15, page 72)

- Combustibles in the Ash

  No correlation with coal properties was observed. (Figures 5-11, 5-12, 5-13, pages 55, 56 and 57)

- Boiler Efficiency

  Unwashed coal resulted in the lowest boiler efficiency due to a higher combustible heat loss. (Figures 5-14 and 5-15, pages 58 and 60)

PARTICLE SIZE DISTRIBUTION OF FLYASH: Three particle size distribution measurements were made by Brink Cascade Impactor and one by SASS Cyclones on the uncontrolled flyash. At full load, 10% of the sampled flyash was smaller than 3 micrometers. (Figures 5-19 and 5-20, pages 75 and 76)

EFFICIENCY OF MECHANICAL DUST COLLECTOR: Collector efficiency was determined for each test by simultaneous inlet and outlet particulate mass loading determinations. Collector efficiency increased with increasing load and with increasing inlet loading. (Table 5-19, page 77)

SOURCE ASSESSMENT SAMPLING SYSTEM (SASS): Flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements during one full load test on the washed coal. Data will be presented in a separate report at the completion of this test program. (Section 5.6, page 80)

The Test Plan and Emission Data Summary are presented in Tables 2-1 and 2-2 on the following pages. For reference, additional data tables are included in Section 5.7. A "Data Supplement" containing all the unreduced data obtained at Site K is available under separate cover for those who wish to further analyze the data. The "Data Supplement" has the same EPA document number as this report except that it is followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and the National Technical Information Service (NTIS).

TABLE 2-1

OUTLINE OF TESTS CONDUCTED AT SITE K

APPROXIMATE FIRING CONDITIONS			TEST NUMBERS*		
% Design Capacity	% O_2	Overfire Air "H_2O	Washed Coal	Unwashed Coal	Crushed Coal
100	8.5	7.5	6	--	--
"	"	2.5	1, 4	14	--
"	7.5	5.0	7, 8	--	--
"	"	2.5	5	--	--
"	6.0	2.5	11	--	16
75	10.5	2.5	3, 10, 18	13	15
50	12.5	5.0	9	--	--
"	"	2.5	2	12	17

* Parameters measured during each test except Test 18 include O_2, CO_2, CO, NO, uncontrolled particulate loading and controlled particulate loading. Test 18 included O_2, CO_2, NO, SOx and SASS

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TABLE 2-2

EMISSION DATA SUMMARY
TEST SITE K

Test No.	Date	% Design Capacity	Coal*	Excess Air, %	O_2 % dry	CO_2 % dry	CO ppm dry	NO ppm dry	NO as NO_2 lb/10^6 Btu	SOx lb/10^6 Btu	Particulate Boiler Out lb/10^6Btu	Particulate D.C. Out lb/10^6Btu
1	10/11/79	97	1	67	8.8	9.6	537	240	0.326	--	1.240	0.199
2	10/13/79	50	1	174	13.7	6.0	339	226	0.311	--	0.737	0.190
3	10/15/79	74	1	100	10.9	8.0	222	290	0.392	--	0.799	0.226
4	10/16/79	100	1	59	8.2	9.7	275	228	0.309	--	0.758	0.148
5	10/24/79	96	1	51	7.5	10.0	208	214	0.285	--	0.755	0.158
6	10/24/79	95	1	60	8.3	9.6	70	258	0.362	--	0.655	0.134
7	10/25/79	101	1	48	7.2	10.6	126	214	0.294	--	0.850	0.129
8	10/26/79	100	1	49	7.3	10.4	105	236	0.320	--	0.639	0.112
9	10/27/79	41	1	149	13.0	6.1	187	223	0.303	--	0.477	0.144
10	10/29/79	74	1	85	10.1	8.1	250	238	0.318	--	0.707	0.118
11	10/30/79	102	1	40	6.4	10.9	182	235	0.315	--	0.571	0.124
12	11/06/79	59	2	148	12.9	6.7	318	302	0.416	--	1.251	0.239
13	11/06/79	77	2	113	11.6	7.0	479	224	0.312	--	2.060	0.197
14	11/07/79	101	2	62	8.5	9.1	313	261	0.355	--	2.202	0.161
15	11/08/79	73	3	84	10.0	8.4	237	200	0.277	--	1.127	0.147
16	11/09/79	102	3	37	6.0	11.1	440	200	0.273	--	1.231	0.140
17	11/10/79	56	3	98	10.8	7.7	182	209	0.291	--	0.698	0.144
18	11/12/79	78	1	81	9.8	8.6	--	209	0.284	1.159	--	--

* 1 - Washed Coal; 2 - Unwashed Coal; 3 - Crushed Coal

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3.0 DESCRIPTION OF FACILITY TESTED AND COALS FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site K. The coals utilized in this test series are also discussed.

3.1 BOILER K DESCRIPTION

Boiler K was built by Riley Stoker Corporation in 1976. This unit is a type VO boiler designed for 200 psig, and capable of a maximum continuous capacity of 50,000 pounds of steam per hour at 125 psig and saturated temperature. The unit has a Riley traveling grate stoker. Coal is mass fed to the front end of the grate and ash is continuously discharged at the back end. There is no suspension burning. Undergrate air can be controlled in six zones. Design data on the boiler and stoker are presented in Table 3-1.

The boiler is equipped with an economizer and a dust collector. There is no flyash reinjection.

3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler K consists of a row of air jets on the front wall, five feet above the grate and 30° below horizontal. The overfire air is supplied by an independent fan with maximum flow producing 7.5" H_2O pressure at the jets. Normal overfire air operating pressure during testing was 2.5" H_2O. This low setting was used because it had been recommended by the Riley startup man.

TABLE 3-1

DESIGN DATA
TEST SITE K

BOILER:	Manufacturer	Riley Stoker Corp.
	Type	VO
	Boiler Heating Surface	6,669 ft^2
	Design Pressure	200 psig
	Tube Diameter	3-1/4 "
FURNACE:	Volume	2,614 ft^3
STOKER:	Manufacturer	Riley Stoker Corp.
	Type	Traveling Grate
	Width	10'0"
	Length	16'0"
	Effective Grate Area	160 ft^2
HEAT RATES:	Steam Flow	50,000 lbs/hr
	Input to Furnace*	69 $x10^6$Btu/hr
	Furnace Width Heat Release*	6.9 $x10^6$Btu/hr-ft
	Grate Heat Release*	424,000 Btu/hr-ft^2
	Furnace Liberation	26,200 Btu/hr-ft^3

* The heat input and heat release rates were determined from coal feed rates and are not necessarily those of the manufacturer.

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3.3 TEST PORT LOCATIONS

Emission measurements were made at two locations -- at the boiler outlet (uncontrolled particulate emissions) and at the dust collector outlet (controlled particulate emissions). The locations of these sample sites are shown in Figure 3-1. Their geometry is shown in Figure 3-2.

Whenever particulate loading was measured it was done simultaneously at both locations using 24-point traverses. Gaseous measurements of O_2, CO_2, CO and NO were obtained by pulling samples individually and compositely from six probes distributed along the width of the boiler outlet and from one probe that was placed in each of the three sampling ports at the dust collector outlet. NO_2 and unburned hydrocarbons were measured by pulling sample through a heated line attached to one of the middle gaseous probes at the boiler outlet. SOx measurements and SASS samples for organic and trace element determinations were obtained from single points within the boiler outlet duct.

3.4 COALS UTILIZED

Three forms of coal from one mine were test fired at Site K. All three were from the Brilliant Coal Company in Brilliant, Alabama. The primary coal was a washed coal, sized at 1-1/4x0 with low fines.

For test purposes, a quantity of unwashed coal from the same mine was ordered. The unwashed coal was higher in ash and lower in heating value. It was reported to have a high clay content. This coal caused some problems with the coal conveyor system. Rocks in the coal were shearing pins in the conveyor. Despite this problem and its unfamiliarity to the operators, three tests were successfully completed on it.

The third coal is referred to as the crushed coal in this report. The plant was equipped with a coal crusher which was ordinarily bypassed. Permission was obtained to run a quantity of the washed coal through this crusher to reduce its top size to 3/4 inch and increase its fines.

Coal samples were obtained from the coal scales apron feeder during each test. These samples were sent to an independent laboratory for

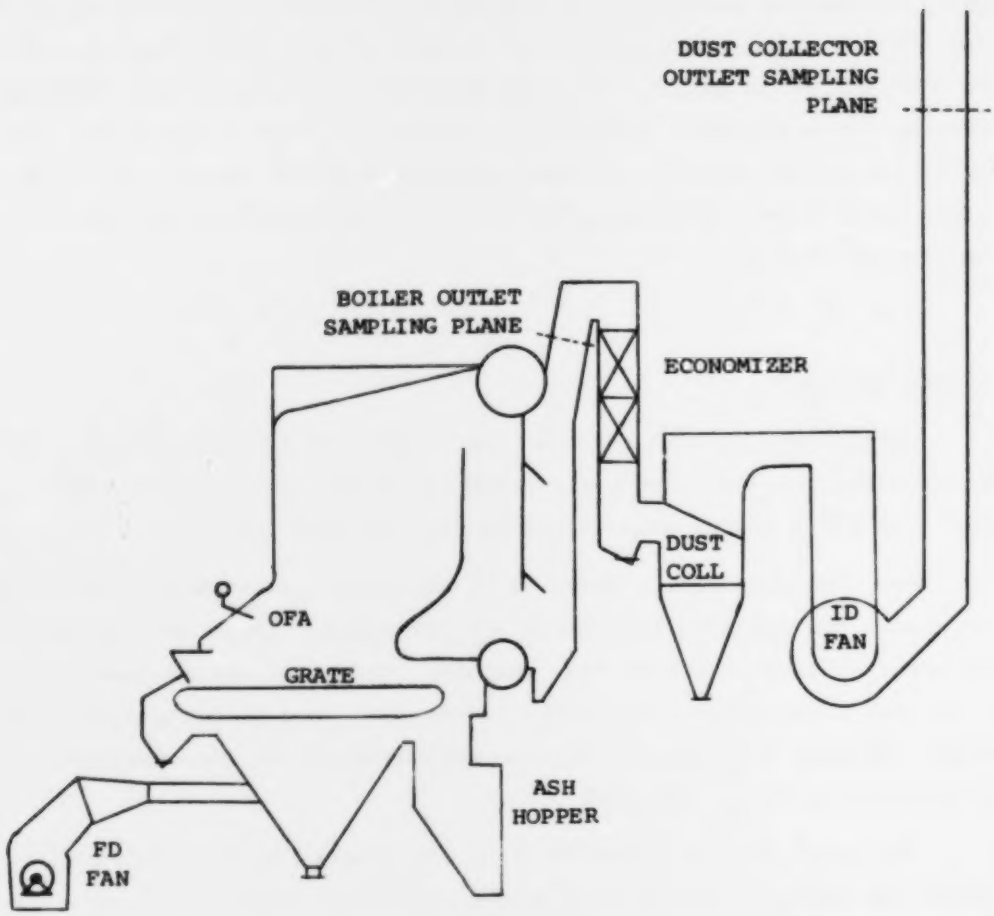

Figure 3-1. Boiler K Schematic

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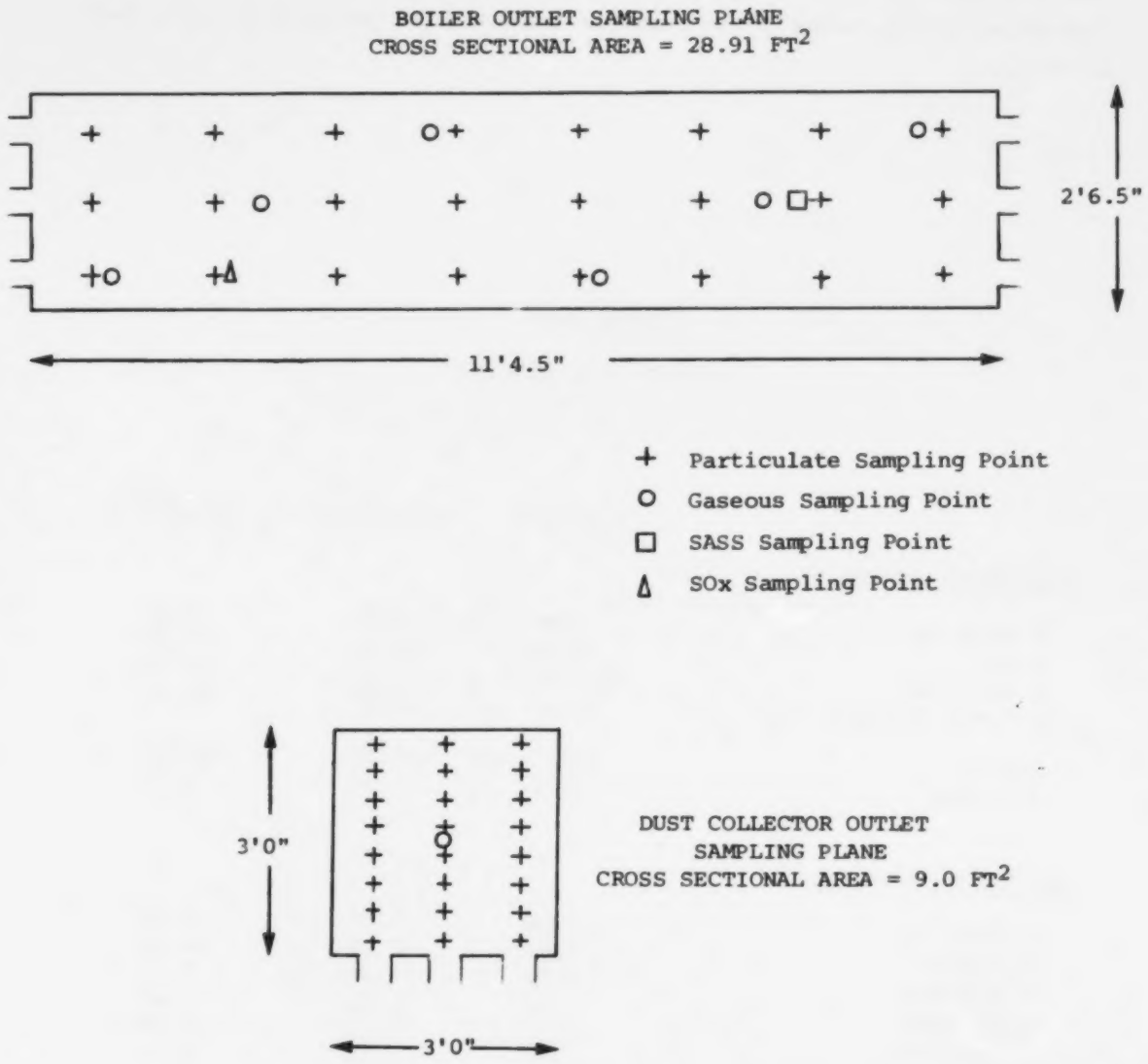

Figure 3-2. Boiler K Sample Plane Geometry

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proximate analysis. One sample of each coal was also analyzed for ultimate analysis, minerals in the ash, ash fusion temperature, hardgrove grindability, free swelling index and sulfur forms. The data are summarized in Table 3-2. Individual sample analysis are found in Section 5.2, Tables 5-9, 5-10, 5-11 and 5-12.

TABLE 3-2

AVERAGE COAL ANALYSIS
TEST SITE K

	Washed	Unwashed	Crushed
PROXIMATE (As Rec'd)*			
% Moisture	6.49	6.19	7.35
% Ash	4.14	10.24	4.68
% Volatile	37.46	33.64	36.72
% Fixed Carbon	51.91	49.88	51.25
Btu/Lb	13237	12280	12994
% Sulfur	1.11	1.01	1.31
ULTIMATE (As Rec'd)**			
% Moisture	6.80	4.76	5.84
% Carbon	73.85	72.21	74.25
% Hydrogen	5.00	4.68	4.97
% Nitrogen	1.55	1.44	1.42
% Chlorine	0.07	0.05	0.06
% Sulfur	1.39	1.10	0.94
% Ash	3.91	7.98	4.15
% Oxygen (Diff)	7.43	7.75	8.37

* Proximate data are average of several samples

** Ultimate data are from single sample

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4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and the sampling procedures followed to assure that accurate, reliable data were collected.

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and gaseous hydrocarbons (HC).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

Constituent:	Nitric Oxide/Total Oxides of Nitrogen (NO/NOx)
Analyzer:	Thermo Electron Model 10 Chemiluminescent Analyzer
Range:	0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO
Accuracy:	±1% of full scale

Constituent:	Carbon Monoxide
Analyzer:	Beckman Model 315B NDIR Analyzer
Range:	0-500 and 0-2000 ppm CO
Accuracy:	±1% of full scale

Constituent:	Carbon Dioxide
Analyzer:	Beckman Model 864 NDIR Analyzer
Range:	0-5% and 0-20% CO_2
Accuracy:	$\pm$1% of full scale

Constituent:	Oxygen
Analyzer	Teledyne Model 326A Fuel Cell Analyzer
Range:	0-5, 10, and 25% O_2 full scale
Accuracy:	$\pm$1% of full scale

Constituent:	Hydrocarbons
Analyzer:	Beckman Model 402 Flame Ionization Analyzer
Range:	5 ppm full scale to 10% full scale
Accuracy:	$\pm$1% of full scale

Oxides of nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications:
- Accuracy 1% of full scale
- Span stability $\pm$1% of full scale in 24 hours
- Zero stability $\pm$1 ppm in 24 hours
- Power requirements 115$\pm$10V, 60 Hz, 1000 watts
- Response 90% of full scale in 1 sec. (NOx mode), 0.7 sec. NO mode
- Output 4-20 ma

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Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon Monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications:
Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications:
- Precision ±1% of full scale
- Response 90% in less than 40 sec.
- Sensitivity 1% of low range
- Linearity ±1% of full scale
- Ambient temperature range 32-125°F
- Fuel cell life expectancy 40,000%-hours
- Power requirement 115 VAC, 50-60 Hz, 100 watts
- Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The same is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as CH_4.

Specifications:
- Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4
- Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1
- Response time 90% full scale in 0.5 sec.
- Precision ±1% of full scale
- Electronic stability ±1% of full scale for successive identical samples

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Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requriements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

4.1.2 Recording Instruments

The Output of the four analyzers is displayed on front panel meters and are simultaneously recorded on a Texas Instrument Model FLO4W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

4.1.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The following sections describe the system and its components. The entire gas sampling and conditioning system shown schematically in Figure 4-1 is contained in the emission test vehicle.

4.1.4 Gaseous Emission Sampling Techniques

Boiler access points for gaseous sampling are selected in the same sample plane as are particulate sample points. Each probe consists of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter is attached to each probe for removal of particulate material.

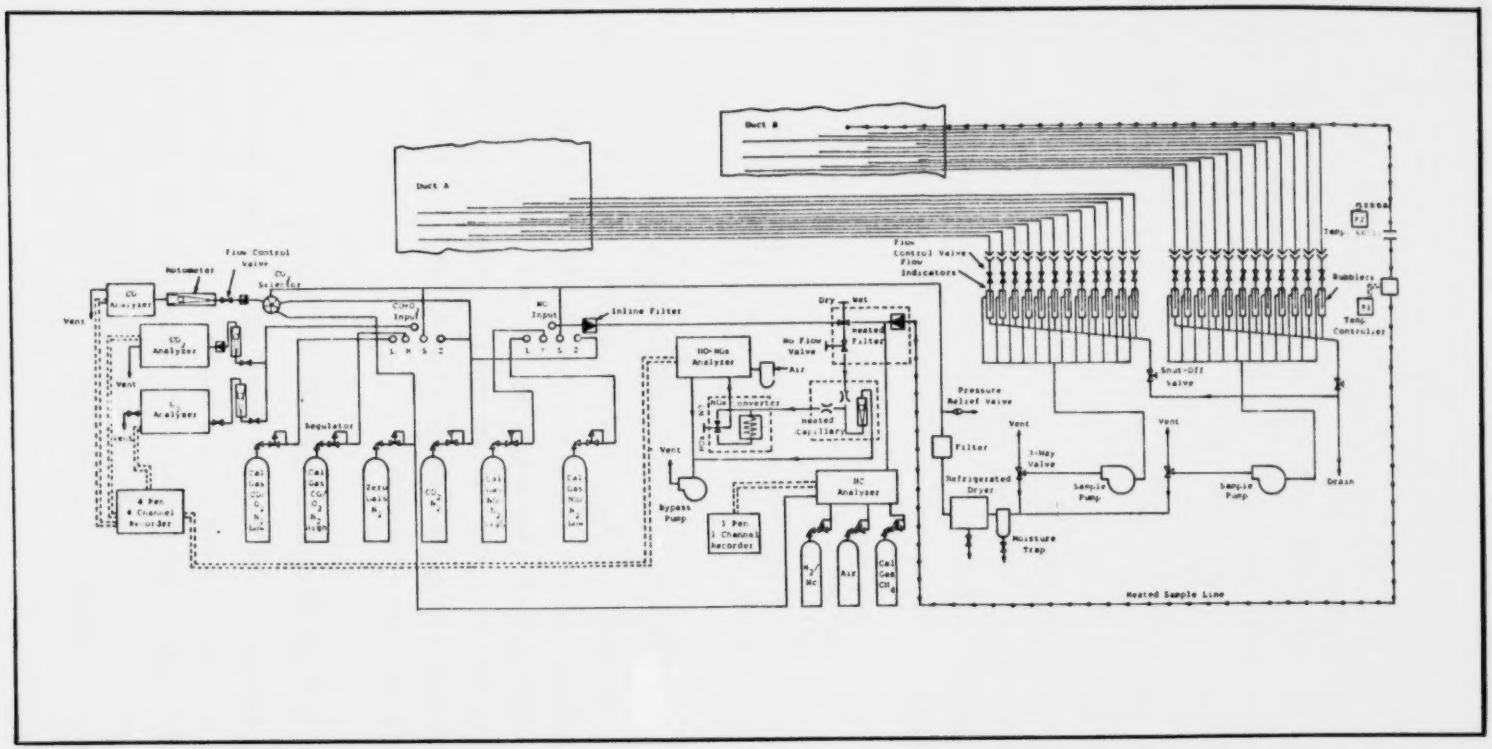

Figure 4-1. Flow Schematic of Mobile Flue Gas Monitoring Laboratory

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Gas samples to be analyzed for O_2, CO_2, CO and NO are conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines. After passing through bubblers for flow control, the samples pass through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas is split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples may be drawn both individually and/or compositely from all probes during each test. The average emission values are reported in this report.

4.2 SULFUR OXIDES (SOx) MEASUREMENT AND PROCEDURES

Measurement of SO_2 and SO_3 concentrations is made by wet chemical analysis using both the "Shell-Emeryville" method and EPA Method 6. In the Shell-Emeryville method the gas sample is drawn from the stack through a glass probe (Figure 4-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 4-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Some of the sulfur trioxide is removed by the first absorber, while the remainder, which passes through as sulfuric acid mist, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isopropyl alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way.

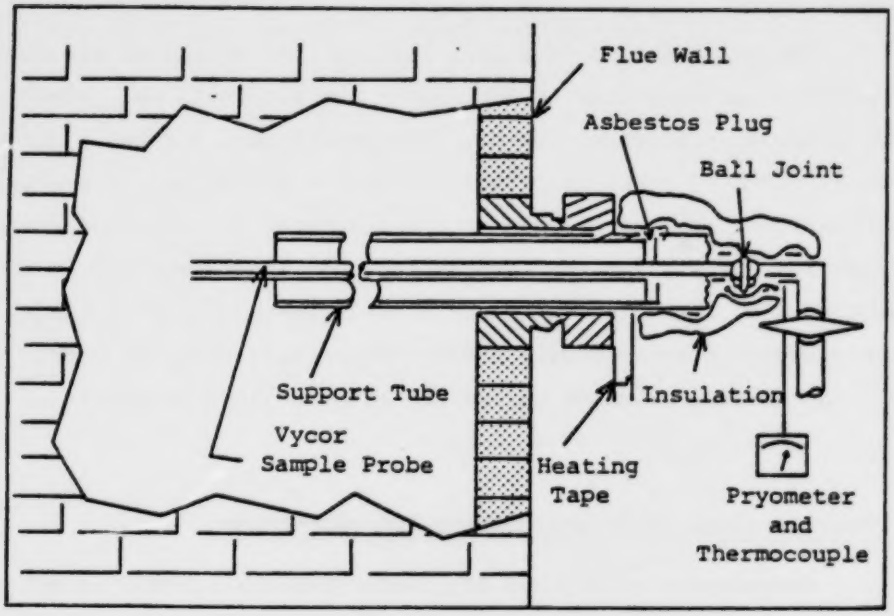

Figure 4-2. SOx Sample Probe Construction

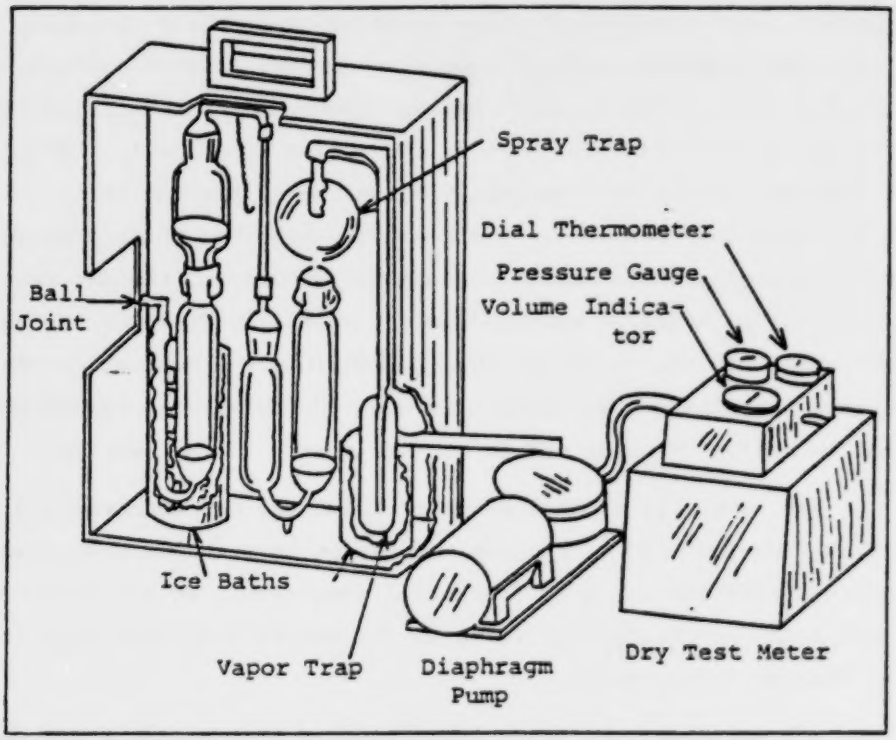

Figure 4-3. Sulfur Oxides Sampling Train

The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

EPA Method 6, which is an alternative method for determining SO_2 (Figure 4-4), employs an impinger train consisting of a bubbler and three midget impingers. The bubbler contains isopropanol. The first and second impingers contain aqueous hydrogen peroxide. The third impinger is left dry. The quartz probe and filter used in the Shell-Emeryville method is also used in Method 6.

Method 6 differs from Shell-Emeryville in that Method 6 requires that the sample rate be proportional to stack gas velocity. Method 6 also differs from Shell-Emeryville in that the sample train in Method 6 is purged with ambient air, instead of nitrogen. Sample recovery involves combining the solutions from the first and second impingers. A 10 ml aliquot of this solution is then titrated with standardized barium perchlorate.

Two repetitions of Shell-Emeryville and two repetitions of EPA Method 6 were made during each test.

4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-5). This system which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

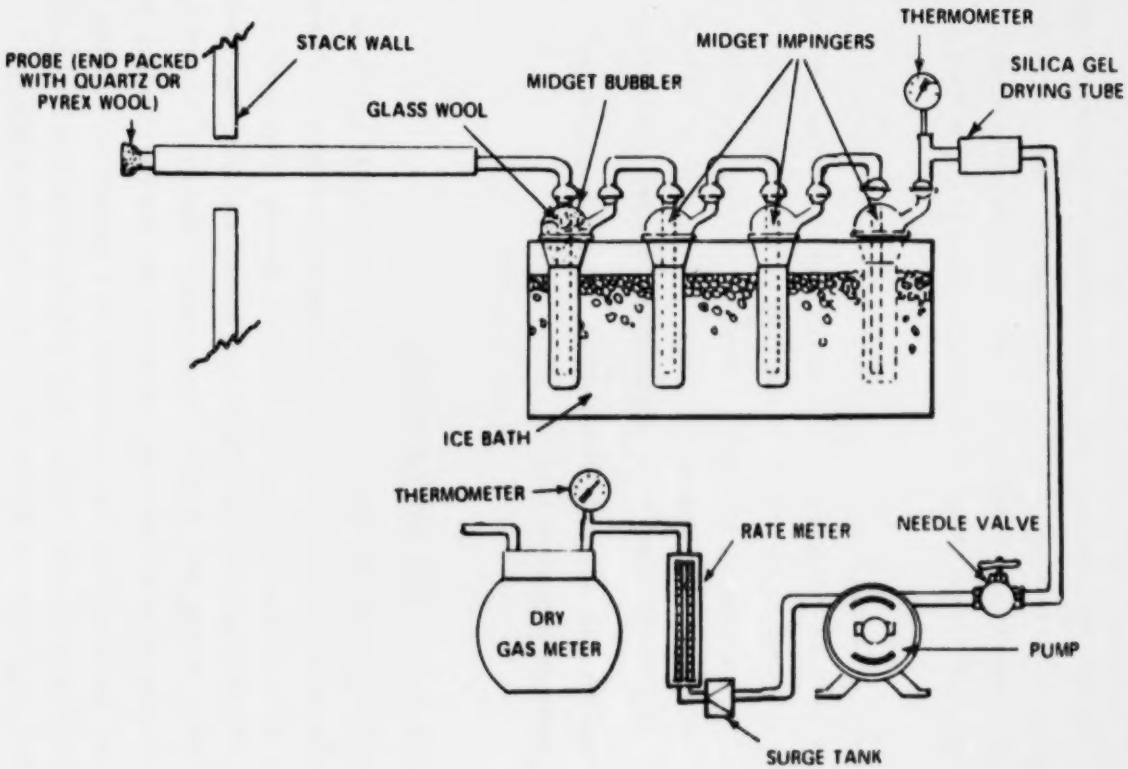

Figure 4-4. EPA Method 6 Sulfur Oxide Sampling Train

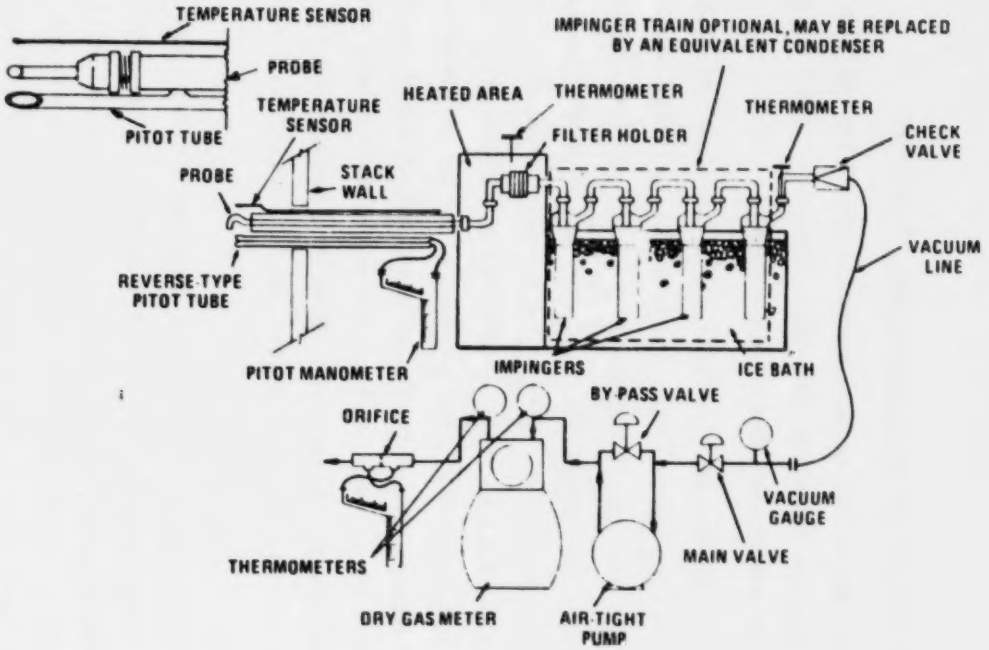

Figure 4-5. EPA Method 5 Particulate Sampling Train

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to $\pm$0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

4.4 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURES

Particle size distribution was measured using two different methods. These are the Brink Cascade Impactor and SASS cyclones. Each of these particle sizing methods has its advantages and disadvantages.

Brink. The Brink cascade impactor is an in-situ particle sizing device which separates the particles into six size classifications. It has the advantage of collecting the entire sample. That is, everything down to the collection efficiency of the final filter is included in the analysis. It has, however, some disadvantages. If the particulate matter is spatially stratified within the duct, the single-point Brink sampler will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is the instrument's small classification range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diameter). Both are inadequate for the job at hand. The particles being collected at the boiler outlet are often as large as the sample nozzle.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02-.07 ft^3/min rate at stack conditions. Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined ΔP for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 4-6.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizer but it includes three calibrated cyclones which can be used as such. The SASS train is a single point in-situ sampler. Thus, it is on a par with cascade impactors. Because it is a high volume sampler and samples are drawn through large nozzles (0.25 to 1.0 in.), it has an advantage over the Brink cascade impactor where large particles are involved. The cut points of the three cyclones are 10, 3 and 1 micrometers. A detailed description of the SASS train is presented in Section 4-8.

4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site K were taken during each test from the unit's coal scale. The samples were processed and analyzed for both size consistency and chemical composition. The use of the coal scale as a sampling station has two advantages. It is close enough to the furance that the coal sampled simultaneously with testing is representative of the coal fired during the testing. Also, because of the construction of the coal scale, it is possible to collect a complete cut of coal off the scales' apron feeder thus insuring a representative size consistency.

In order to collect representative coal samples, a sampling tray having a twenty pound capacity was custom built. The tray has the same width as the apron feeder belt and can be moved directly under the belt's discharge end to catch all of the coal over a short increment of time (approximately five seconds).

The sampling procedure is as follows. At the start of testing one increment of sample is collected from the apron feeder. This is repeated several times during the test (three to five hours duration) so that a six increment sample is obtained. The sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty pound samples are obtained.

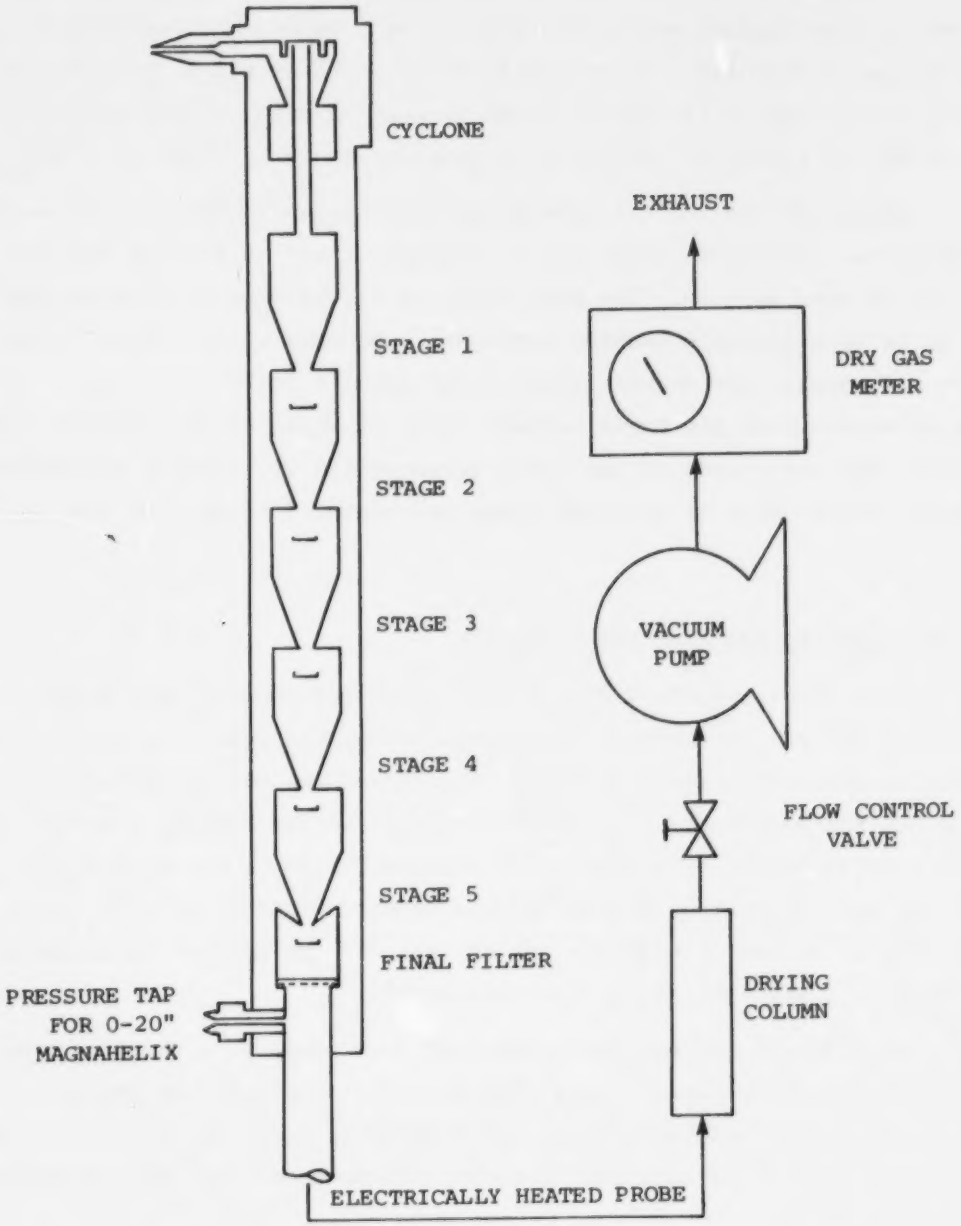

Figure 4-6. Brink Cascade Impactor Sampling Train

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The sample to be used for sieve analysis is air dried overnight and weighed. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

4.6 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cylcone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site K the bottom ash samples were collected in several increments from the stoker ash pit at completion of testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination. Multiclone ash samples were taken from ports

near the base of the multiclone hopper. This sample, approximately two quarts in size, was sent to Commercial Testing and Engineering Company for combustible determination.

4.7 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash and combustibles in the flyash leaving the boiler.

4.8 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-7). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

Together with a filter, a fourth cut (<1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone system. The gas treatment system is composed of four primary components:

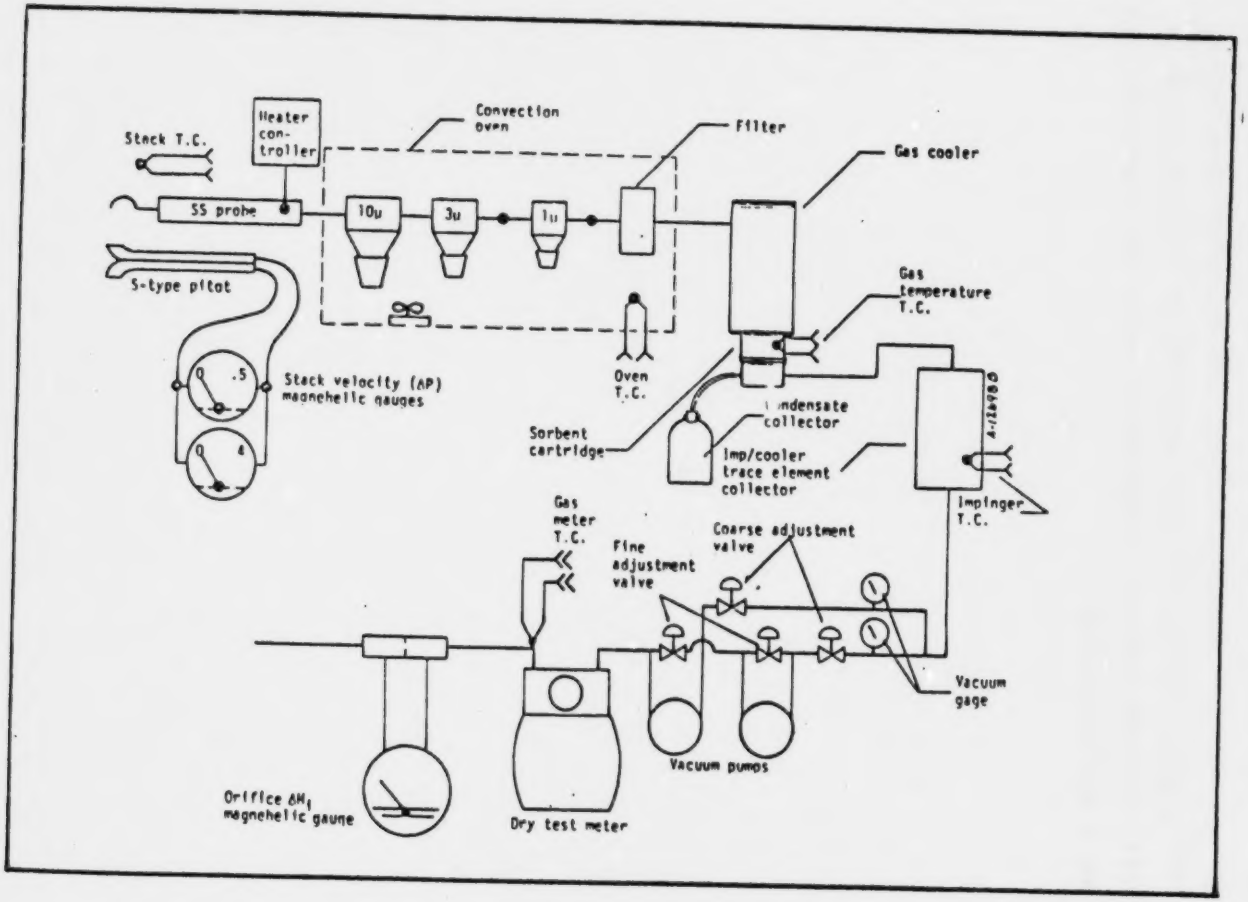

Figure 4-7. Source Assessment Sampling (SASS) Flow Diagram

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the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

5.0 TEST RESULTS AND OBSERVATIONS

This section presents the results of tests performed on Boiler K. Observations are made regarding the influence on efficiency and on gaseous and particulate emissions as the control parameters are varied. Eighteen defined tests were conducted over a one-month period to develop this data. Tables 2-1 and 2-2 in the Executive Summary, and Tables 5-22 through 5-25 at the end of this section are included for reference.

5.1 OVERFIRE AIR

The overfire air system in Boiler K consisted of a single row of air jets on the front water wall. Air flow to these jets was controllable up to a maximum of about 7.5 inches water pressure. However, normal operating procedure at this site was to maintain overfire air flow at about 2.5 inches water pressure over the full load range.

In order to investigate the effect of overfire air on emissions and efficiency, three test series were conducted in which overfire air was the primary variable. Figure 5-1 shows the overfire air pressure for each test as a function of grate heat release. The high overfire air tests are identified in this figure and in all subsequent figures by solid symbols.

The test results are presented in Table 5-1 and discussed in the following paragraphs. In general, increased overfire air effectively dropped the flyash combustible level, the carbon monoxide concentration and the particulate mass loading, but had little or no effect on the nitric oxide concentration or the boiler efficiency.

5.1.1 Particulate Loading vs Overfire Air

Uncontrolled particulate mass loading dropped an average 20% when overfire air pressure was increased. Although 20% is significant, there is a degree of uncertainty associated with this number. The data, presented in Table 5-2, shows that in one of the five test sets, particulate mass loading actually increased 13% when overfire air pressure increased.

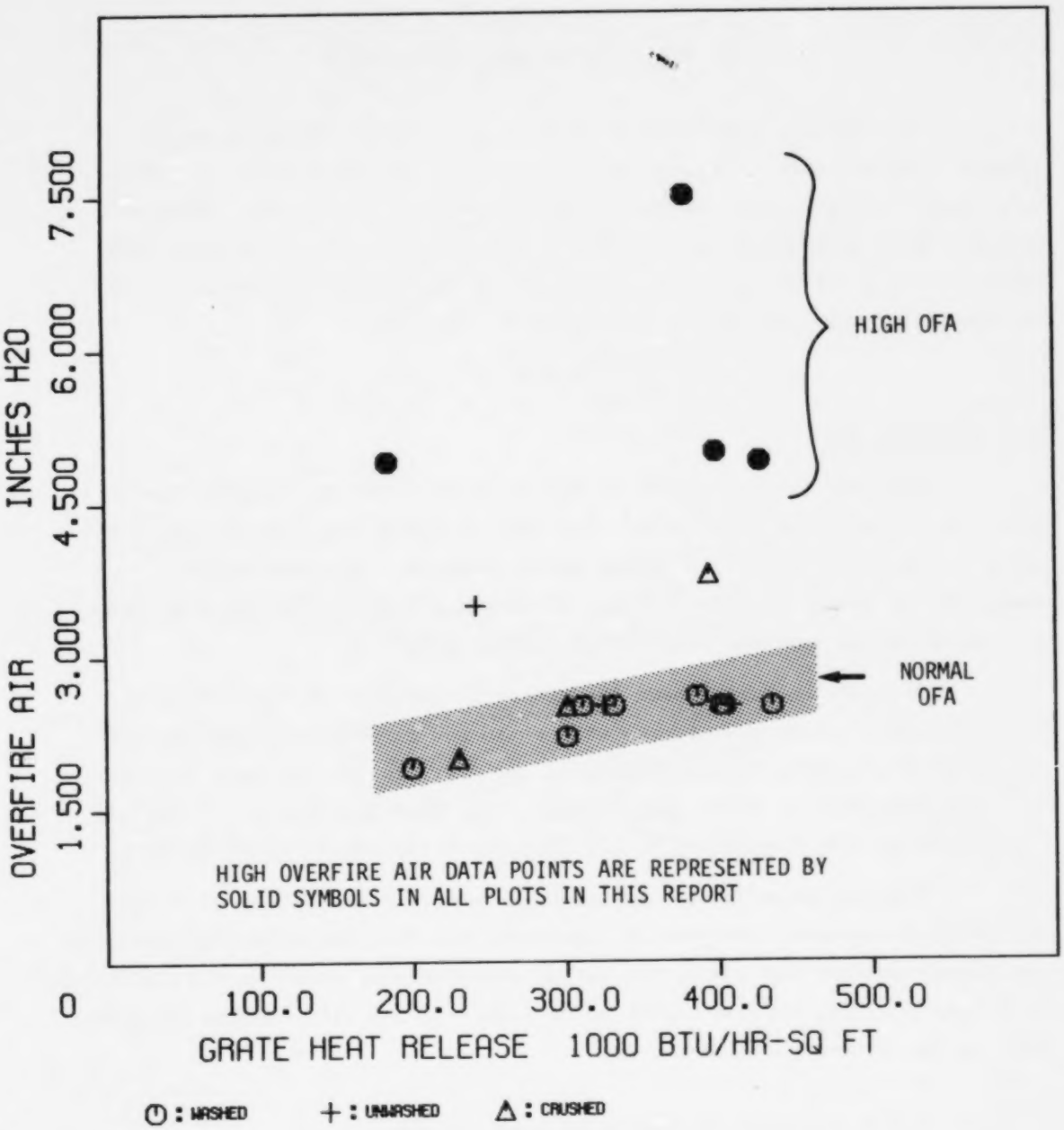

FIG. 5-1
OVERFIRE AIR VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

TABLE 5-1

EFFECT OF OVERFIRE AIR ON EMISSIONS AND EFFICIENCY
TEST SITE K

	FULL LOAD, HIGH O_2			FULL LOAD, MED O_2			LOW LOAD NORM O_2	
TEST No.	1	4	6	5	7	8	2	9
Description	Low OFA	Low OFA	High OFA	Low OFA	High OFA	High OFA	Low OFA	High OFA
FIRING CONDITIONS								
Overfire Air Pressure, "H_2O	2.5	2.5	7.5	2.6	5.0	4.9	1.9	4.9
Load, % of Capacity	97	100	95	96	101	100	50	41
Grate Heat Release, 10^3Btu/hr-ft^2	401	405	380	386	399	428	201	185
Coal Description	Washed	Washed	Washed	Washed	Washed	Washed	Washed	Washed
Coal Fines, % Passing 1/4"	22	22	16	16	21	19	19	31
Excess Air, %	67	59	60	51	48	49	174	149
UNCONTROLLED EMISSIONS								
Particulate Loading, lb/10^6Btu	1.240	0.758	0.655	0.755	0.850	0.639	0.737	0.477
Combustible Loading, lb/10^6Btu	0.399	0.278	0.193	0.308	0.230	0.188	0.265	0.114
Inorganic Ash Loading, lb/10^6Btu	0.841	0.480	0.462	0.447	0.621	0.451	0.472	0.363
Combustibles in Flyash, %	32.2	36.7	29.4	40.8	27.0	29.4	36.0	24.0
Combustibles in Bottom Ash, %	27.6	47.6	60.0	69.1	37.9	39.5	23.9	75.5
O_2, % (dry)	8.8	8.2	8.3	7.5	7.2	7.3	13.7	13.0
CO_2, % (dry)	9.6	9.7	9.6	10.0	10.6	10.4	6.0	6.1
CO, ppm @ 3% O_2	537	275	70	208	126	105	339	187
NO, lb/10^6Btu	0.326	0.309	0.321	0.285	0.294	0.320	0.311	0.303
CONTROLLED EMISSIONS								
Particulate Loading, lb/10^6Btu	0.199	0.148	0.134	0.158	0.129	0.112	0.190	0.144
Dust Collector Efficiency, %	84.0	80.5	79.5	79.1	84.8	82.5	74.2	69.8
HEAT LOSSES, %								
Dry Gas	11.01	10.58	11.41	9.82	10.23	10.55	16.37	12.07
Moisture in Fuel	0.49	0.67	0.64	0.54	0.71	0.69	0.63	0.54
H_2O from Combustion of H_2	4.10	4.07	4.23	4.04	4.17	4.15	4.14	4.04
Combustibles in Flyash	0.57	0.40	0.28	0.44	0.33	0.23	0.39	0.16
Combustibles in Bottom Ash	1.83	2.63	5.48	6.72	2.49	2.02	1.14	15.70
Radiation	0.64	0.65	0.65	0.65	0.62	0.62	1.22	1.50
Unmeasured	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Total Losses	20.14	20.47	24.19	23.71	20.05	19.80	25.39	35.51
Boiler Efficiency	79.86	79.53	75.81	76.29	79.95	80.20	74.61	64.49

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TABLE 5-2

PARTICULATE LOADING VS OVERFIRE AIR

Test No.	Overfire Air	Uncontrolled Particulate lb/10^6Btu	% Change	Controlled Particulate lb/10^6Btu	% Change
1	Low (2.5" H_2O)	1.24		0.20	
6	High (7.5" H_2O)	0.66	- 47	0.13	- 33
4	Low (2.5" H_2O)	0.76		0.15	
6	High (7.5" H_2O)	0.66	- 14	0.13	- 9
5	Low (2.6" H_2O)	0.76		0.16	
7	High (5.0" H_2O)	0.85	+ 13	0.13	- 18
5	Low (2.6" H_2O)	0.76		0.16	
8	High (4.9" H_2O)	0.64	- 15	0.11	- 21
2	Low (1.9" H_2O)	0.74		0.19	
9	High (4.9" H_2O)	0.48	- 35	0.14	- 24

The controlled particulate mass loading (dust collector outlet) showed a similar reduction due to increased overfire air pressure. The average reduction at this location was 21%, and the data exhibited greater consistency than at the boiler outlet.

The measured particulate reductions can be attributed in part to a reduction in the combustible fraction of the flyash. The combustible fractions were reduced an average of 25% in these same tests.

Test data are graphically presented in Figures 5-3 and 5-4 of section 5.2. High overfire air tests in these figures are indicated by solid symbols.

5.1.2 Nitric Oxide vs Overfire Air

The nitric oxide (NO) concentration was not influenced by the variable overfire air. This conclusion is best illustrated by Figure 5-7 of section 5.2 which shows the high overfire air data to be of the same magnitude as the low overfire air data under similar conditions of oxygen and grate heat release.

5.1.3 Carbon Monoxide vs Overfire Air

Carbon monoxide (CO) dropped an average 60% when overfire air pressure was increased. This data is presented in Table 5-3, and is graphically illustrated in Figures 5-9 and 5-10 of Section 5.2.

TABLE 5-3

CARBON MONOXIDE VS OVERFIRE AIR

Test No.	Overfire Air ("H_2O)	Carbon Monoxide ppm @ 3% O_2
1	Low (2.5)	537
4	Low (2.5)	275
6	High (7.5)	70
5	Low (2.6)	208
7	High (5.0)	126
8	High (4.9)	105
2	Low (1.9)	339
9	High (4.9)	187

5.1.4 Boiler Efficiency vs Overfire Air

The heat loss due to combustibles in the flyash decreased as overfire air increased. However, this efficiency improvement was small, on the order of 0.2 to 0.3% of the heat input. On this unit, boiler efficiency was reduced by energy loss due to combustibles in the bottom ash which were on the order of 2 to 7%. Since no consistent correlation was found between combustibles in the bottom ash and overfire air, it is concluded that boiler efficiency was not significantly affected by changes in the overfire air pressure.

Data supporting this conclusion is presented in Table 5-4. The data are graphically presented in Figure 5-11 (Combustibles in Flyash), Figure 5-13 (Combustibles in Bottom Ash), and Figures 5-14 and 5-15 (Boiler Efficiency) of Section 5.2.

TABLE 5-4

BOILER EFFICIENCY VS OVERFIRE AIR

Test No.	Overfire Air ("H_2O)	Heat Loss Due to Comb in Flyash, %	Heat Loss Due to Comb in Bottom Ash, %	% Boiler Efficiency
1	Low (2.5)	0.57	1.83	79.86
4	Low (2.5)	0.40	2.63	79.53
6	High (7.5)	0.28	5.48	75.81
5	Low (2.6)	0.44	6.72	76.29
7	High (5.0)	0.33	2.49	79.95
8	High (4.9)	0.23	2.02	80.20
2	Low (1.()	0.39	1.14	74.61
9	High (4.9)	0.16	15.70	64.49

5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

Tests were conducted on Boiler K at loads of 50%, 75% and 100% of the unit's design capacity. At each load, tests were conducted within a range of about 2% excess oxygen. This section profiles emissions and boiler efficiency as a function of these two variables.

The units chosen to present this data are percent oxygen (dry), and grate heat release in Btu/hr-ft^2. Grate heat release, which is proportional to the unit's steam loading, was chosen because it provides a common basis for comparing this unit's emissions with those of other units tested in this program.

The four high overfire air tests are indicated on each plot in this section by solid symbols. Most of the plots also differentiate the three coals by means of distinct symbols.

5.2.1 Excess Oxygen Operating Levels

Figure 5-2 depicts the various conditions of grate heat release and excess oxygen under which tests were conducted on Boiler K. Nine tests were conducted at full load which corresponds to about 400,000 Btu/hr-ft^2 grate area. Five tests were conducted at 75% of capacity or 300,000 Btu/hr-ft^2, and four tests at 50% of capacity or 200,000 Btu/hr-ft^2.

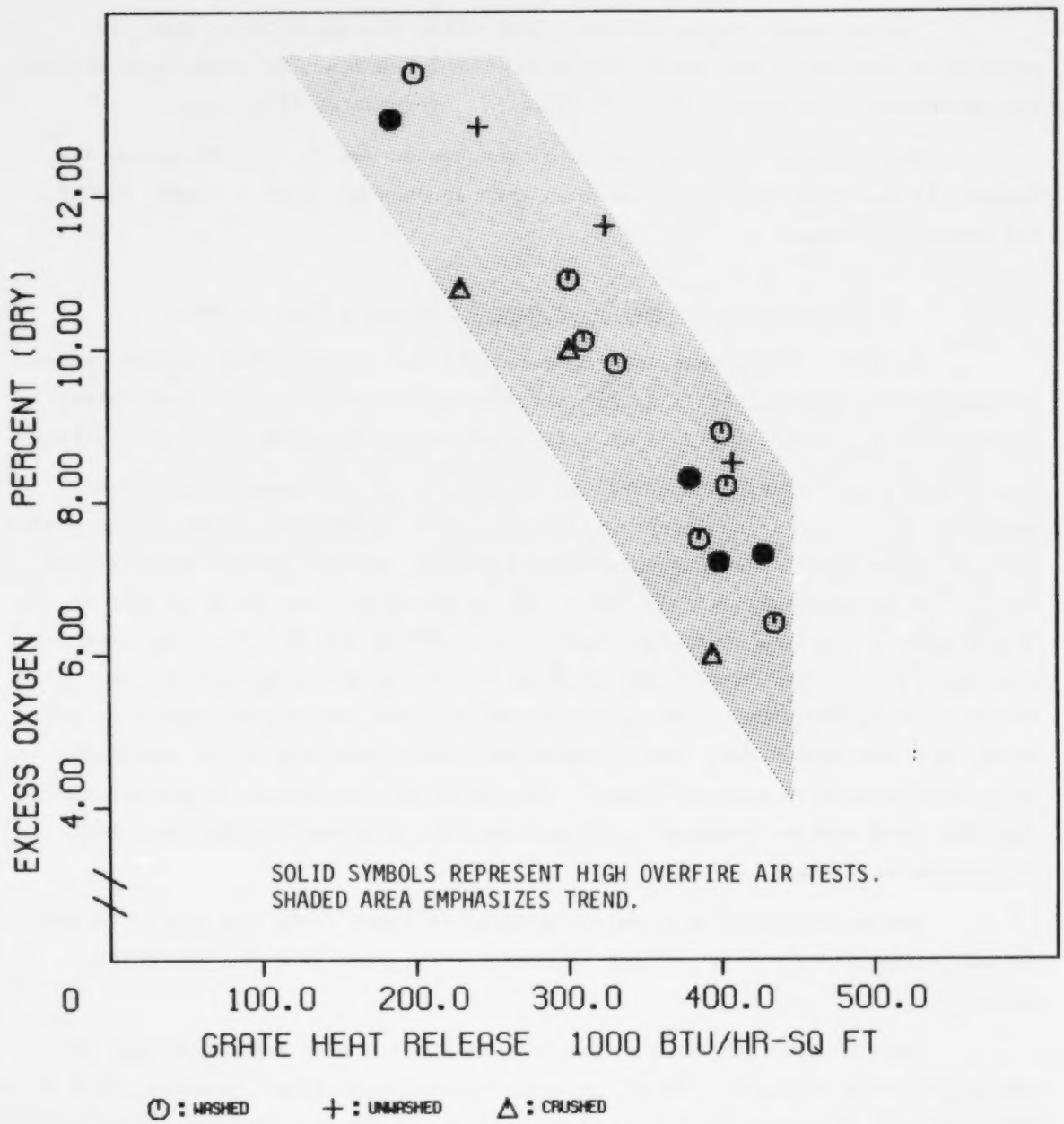

FIG. 5-2
EXCESS OXYGEN VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

Excess oxygen varied within a band which was about 2% O_2 wide, as previously mentioned, and which decreased sharply as load, or grate heat release, was increased. The shaded area of Figure 5-2 accentuates this trend.

The minimum full load excess oxygen tested was 6%, or 37% excess air. Excess air has been determined for each test and may be found in Table 2-2 of the Executive Summary.

5.2.2 Particulate Loading vs Oxygen and Grate Heat Release

The particulate mass loading data obtained at the boiler outlet before the mechanical dust collector is presented as a function of grate heat release in Figure 5-3. This data is often called the uncontrolled particulate loading.

The data is seen to correlate strongly with coal properties. The washed coal exhibited the lowest particulate mass loadings as shown by the shaded area in Figure 5-3. The crushed coal particulate loading was 58% greater than that of the washed coal at full load. This is presumably a direct result of the increase in fines from 20 to 44% passing 1/4" square mesh screen. The unwashed coal had the greatest particulate loading, nearly three times that of the washed coal at full load. The unwashed coal did not have significantly greater fines than the washed coal, but it contained more impurities which apparently were readily carried over as flyash. The unwashed coal contained 14% ash during the full load test as compared to 4% ash for the full load crushed coal test and washed coal tests.

The uncontrolled particulate loading is shown in Figure 5-3 to increase in magnitude as grate heat release increases. This was true for all three coals.

Uncontrolled particulate loading was not found to correlate with the small variations in excess oxygen encountered during testing. However, this is due to a lack of supportive data and does not preclude the likelihood of such a correlation.

The controlled particulate data, i.e., that data obtained after the mechanical dust collector, is presented as a function of grate heat release in Figure 5-4. The controlled and uncontrolled particulate mass loadings were obtained simultaneously during each of the first seventeen tests on Boiler K.

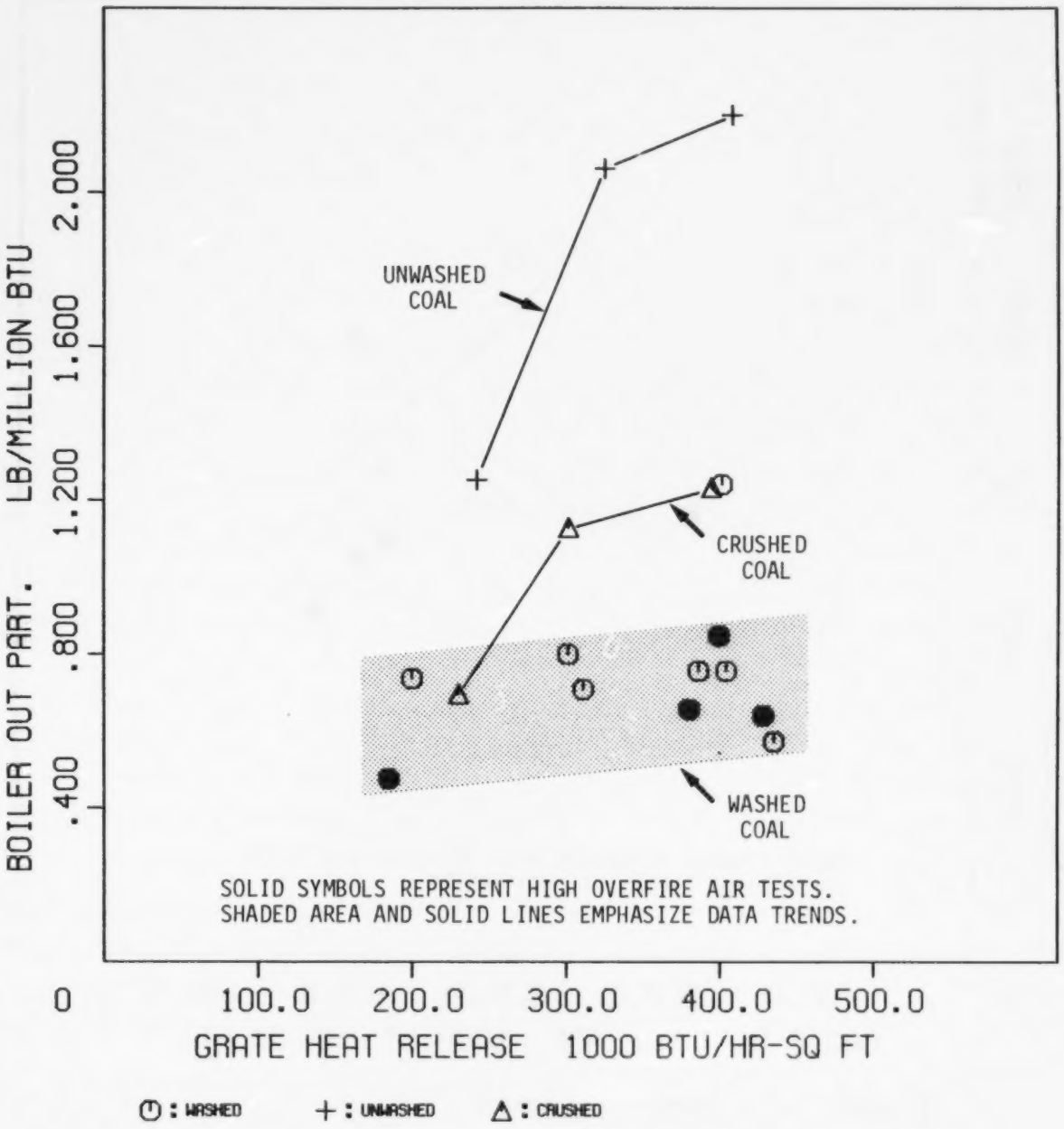

FIG. 5-3

BOILER OUT PART. VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

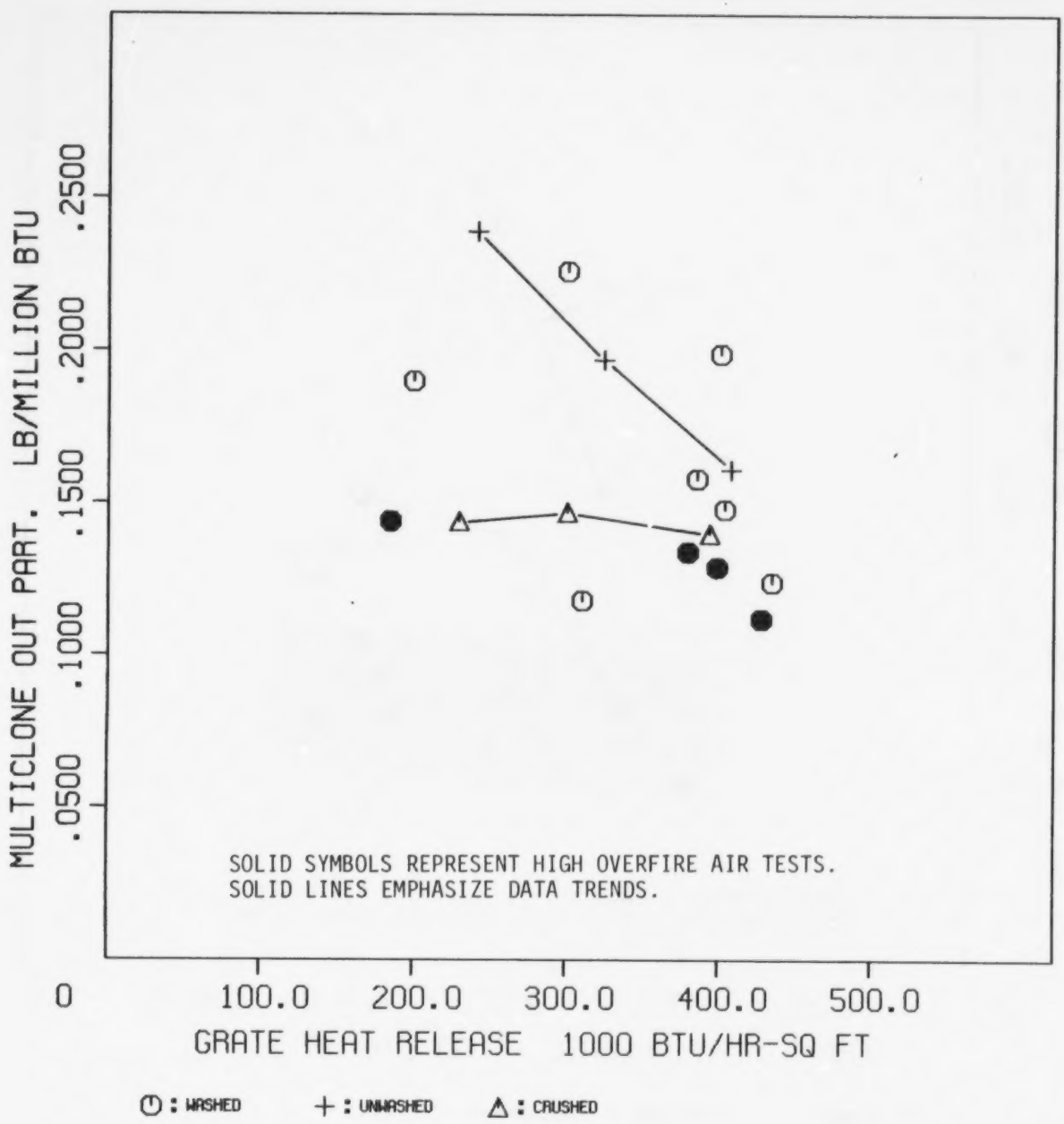

FIG. 5-4

MULTICLONE OUT PART. VS. GRATE HEAT RELEASE
TEST SITE K

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The effect of coal type is not as pronounced after the collector as it was before the collector. The unwashed coal still exhibits greater particulate mass loadings than the crushed coal. The washed coal data, however, are cattered. This scatter simply reflects variations in the efficiency of the dust collector which may or may not be related to coal properties or other operating parameters.

The controlled particulate loading decreases as grate heat release increases. This is probably a result of increased mechanical dust collector efficiency as pressure drop and velocity through the cyclone tubes increases.

As with the uncontrolled particulate mass loading, data are limited regarding the effect of excess oxygen on controlled particulate loading. However, there is clearer evidence at this sample location that increased oxygen, over the limited range tested, does increase the particulate loading. This data is presented for the three load ranges in Figure 5-5. The full load data are shaded to emphasize the trend.

Percent ash carryover was determined for each test and is presented in Table 5-5. The average ash carryover for the seventeen tests was $16 \pm 4\%$. Note that in this report, ash carryover is defined as the amount of non-combustible, non-volatile material found in the flyash compared with the amount of the same material found in the coal, both corrected to a heat input basis. In other words, combustibles in the flyash are excluded.

Stack opacity is related to particulate loading and is, therefore, included in this section. Stack opacity was measured by a transmissometer and the data are presented in Figure 5-6. It is observed that the crushed coal, which contained the greatest fraction of fines, increased the opacity sharply as grate heat release increased. The unwashed coal produced low opacity levels of the same general magnitude as the washed coal. Opacity did not correlate with controlled particulate loading.

5.2.3 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) concentration was measured during each test in units of parts per million (ppm) by volume. The units have been converted to lb $NO_2/10^6$ Btu on a heat input basis so that they will be more easily compared with existing and proposed emission standards. Table 2-2 in the Executive Summary lists the

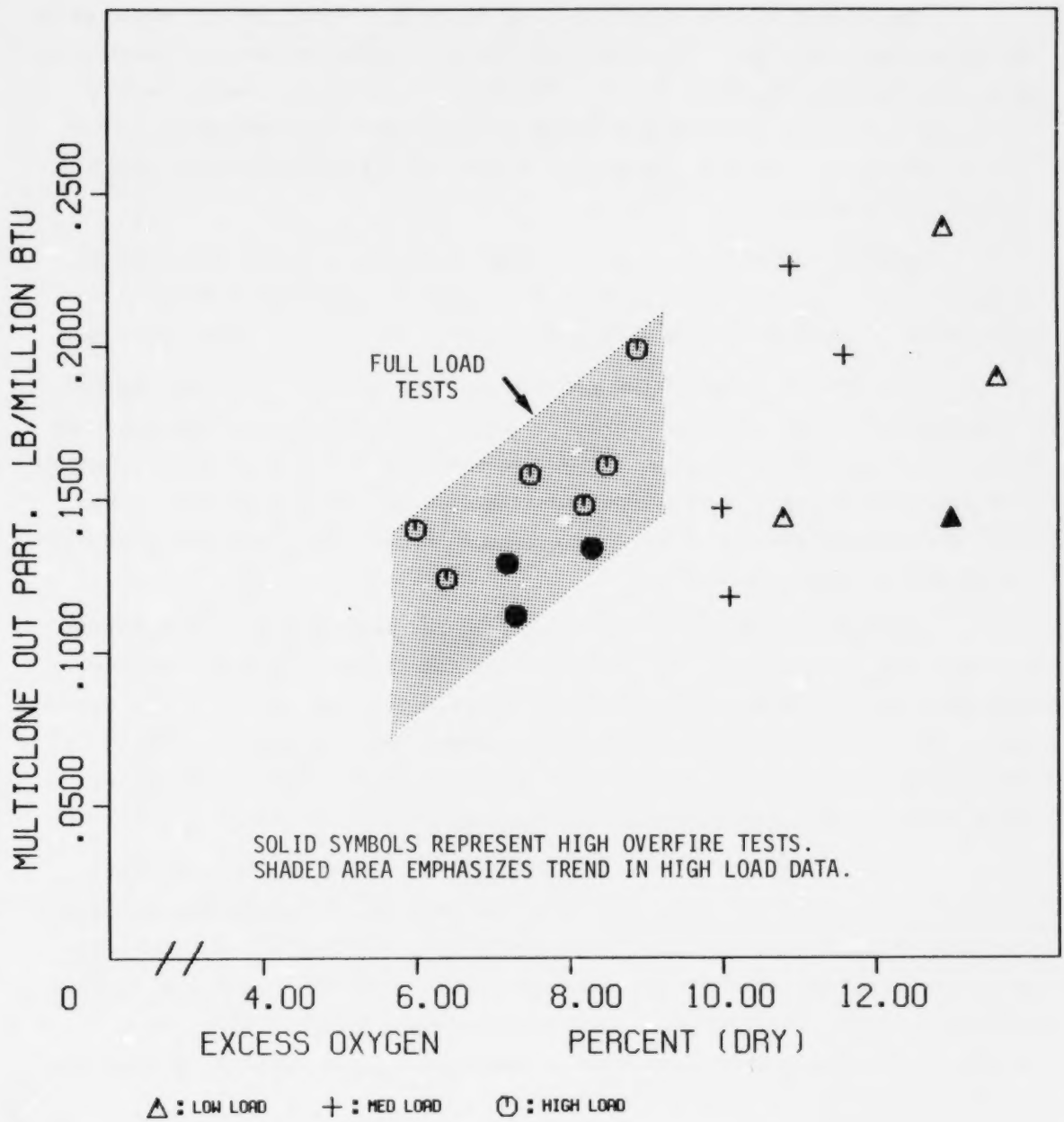

FIG. 5-5
MULTICLONE OUT PART. VS. EXCESS OXYGEN
TEST SITE K

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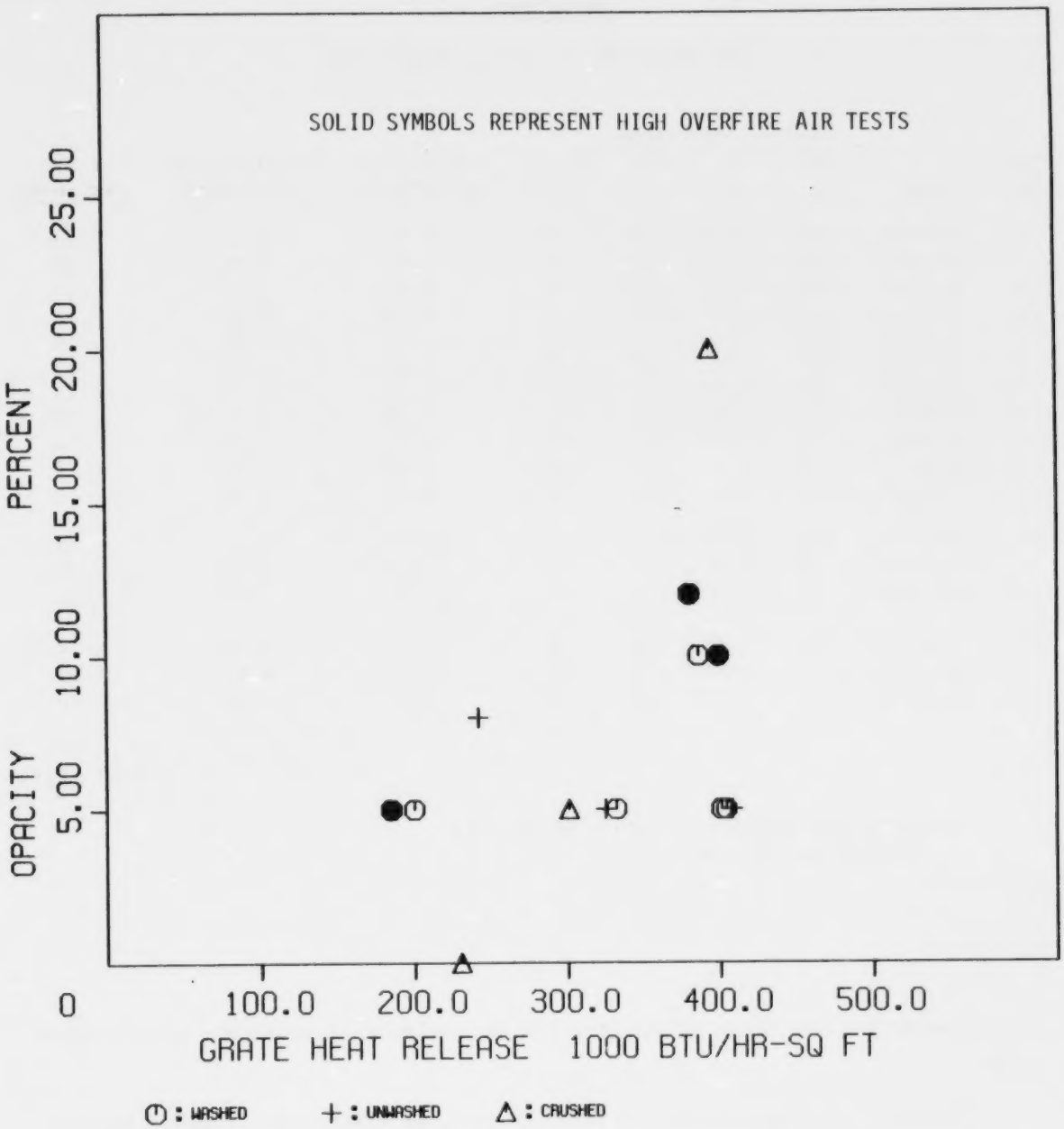

FIG. 5-6

OPACITY VS. GRATE HEAT RELEASE

TEST SITE K

4-15900-548

TABLE 5-5

ASH CARRYOVER VS FIRING CONDITIONS

Test No.	Coal	FIRING CONDITIONS Load %	O_2 %	OFA "	Fines %	Ash in Coal lb/10^6Btu	Ash in Flyash lb/10^6Btu	% Ash Carryover
1	Washed	100	8.8	2.5	22	4.21	0.84	20
4	Washed	100	8.2	2.5	22	2.51	0.48	19
5	Washed	100	7.5	2.6	16	2.56	0.45	17
6	Washed	100	8.3	7.5	16	4.12	0.46	11
7	Washed	100	7.2	5.0	21	3.49	0.62	18
8	Washed	100	7.3	4.9	19	2.62	0.45	17
11	Washed	100	6.4	2.5	21	2.63	0.39	15
3	Washed	75	10.9	2.2	20	3.04	0.54*	18*
10	Washed	75	10.1	2.5	15	3.31	0.47	14
2	Washed	50	13.7	1.9	19	3.99	0.47	12
9	Washed	50	13.0	4.9	31	3.94	0.36	9
14	Unwashed	100	8.5	2.5	22	11.86	1.43	12
13	Unwashed	75	11.6	2.5	32	6.70	1.33	20
12	Unwashed	50	12.9	3.5	23	6.67	0.87	13
16	Crushed	100	6.0	3.8	39	3.19	0.77	24
15	Crushed	75	10.0	2.5	54	3.53	0.76	21
17	Crushed	50	10.8	2.0	39	4.09	0.48	12
							AVG	$16 \pm 4\%$

*Average combustible content, 32.1%, was assumed for Test No. 3.

nitric oxide data in units of ppm for the convenience of those who prefer these units.

Figure 5-7 presents the nitric oxide data as a function of grate heat release under the various excess oxygen conditions encountered during testing. Nitric oxide is relatively invariant with grate heat release on this unit when excess oxygen is not held constant. Average nitric oxide for each of the three load ranges is presented in Table 5-6.

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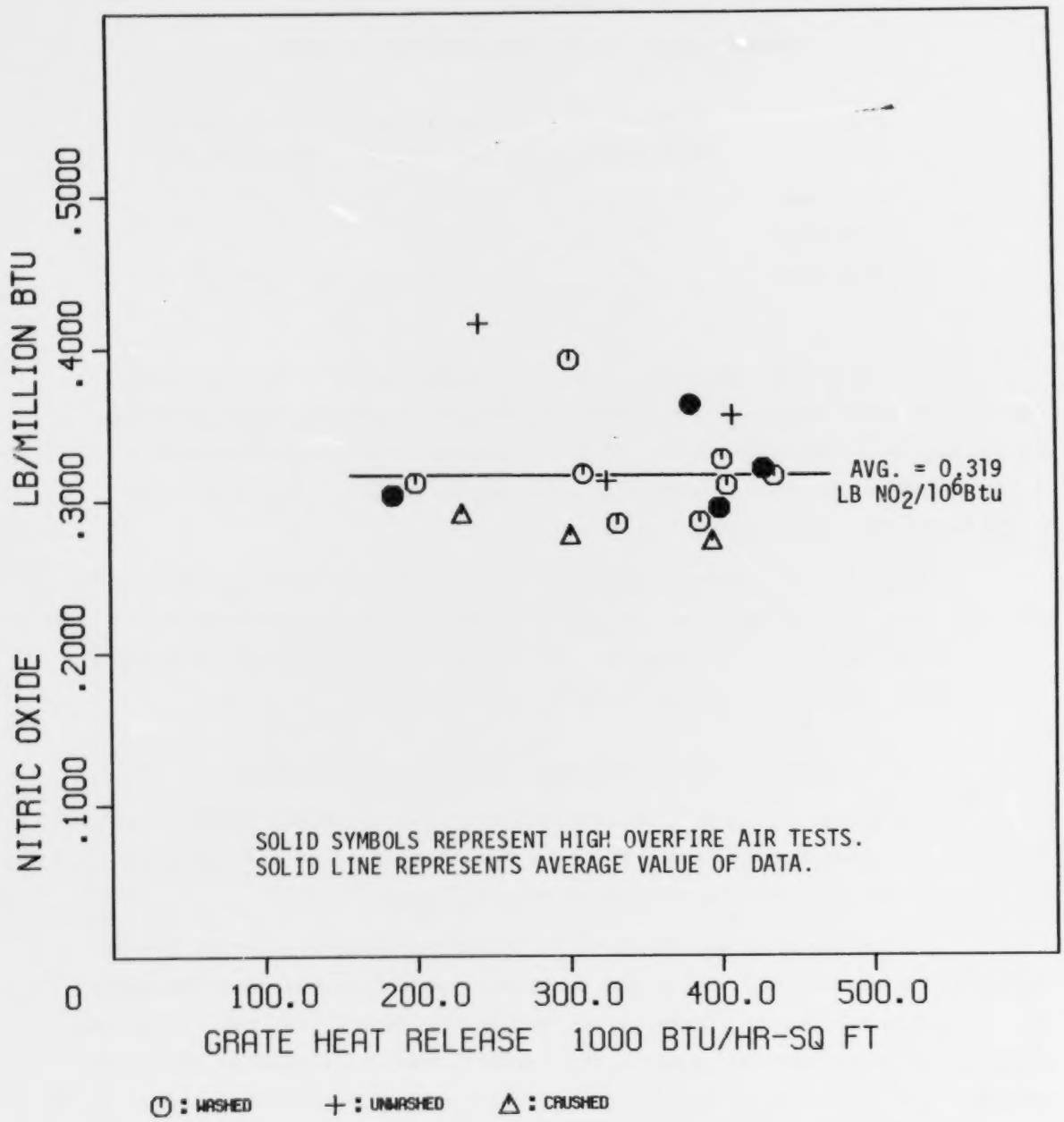

FIG. 5-7
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

TABLE 5-6

AVERAGE NITRIC OXIDE CONCENTRATION VS LOAD

	Number of Data Points	Nitric Oxide lb $NO_2/10^6$Btu	Nitric Oxide ppm @ 3% O_2
100% Load	9	0.316	232
75% Load	5	0.316	232
50% Load	4	0.330	240

Figure 5-8 presents the nitric oxide data as a function of excess oxygen. In this figure, nitric oxide is shown to increase with increasing excess oxygen at constant load. At full load, nitric oxide increases by 0.033 lb/10^6Btu for each one percent increase in oxygen. A line of this slope has been drawn through the data.

Nitric oxide concentrations were not altered by the changes in coal. The fact that crushed coal has the lowest nitric oxide concentrations in Figure 5-7 is due to operation at lower O_2. At similar load and excess oxygen the nitric oxide concentrations were essentially equivalent.

5.2.4 Carbon Monoxide vs Oxygen and Grate Heat Release

The carbon monoxide (CO) concentration was monitored during each test. The data are presented in Figure 5-9 as a function of grate heat release, and in Figure 5-10 as a function of excess oxygen.

Carbon monoxide was found to be highly variable within the general range of 100 to 500 ppm. No trends were observed for carbon monoxide either as a function of load or excess oxygen within the limits examined. Coal type was also found to have no impact. The largest observed influence on carbon monoxide concentration was overfire air, which effectively reduced the CO to its lowest levels.

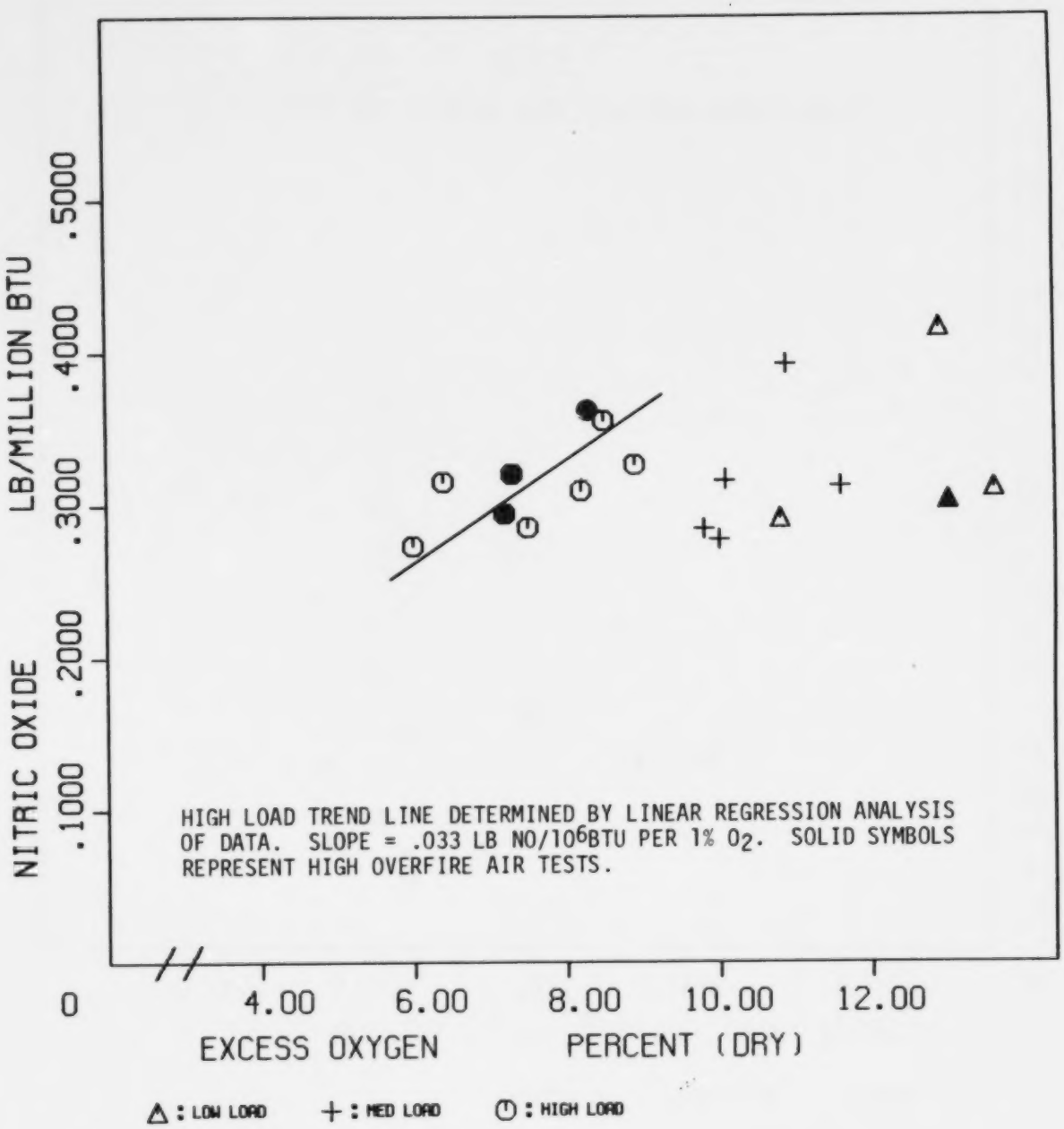

FIG. 5-8
NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE K

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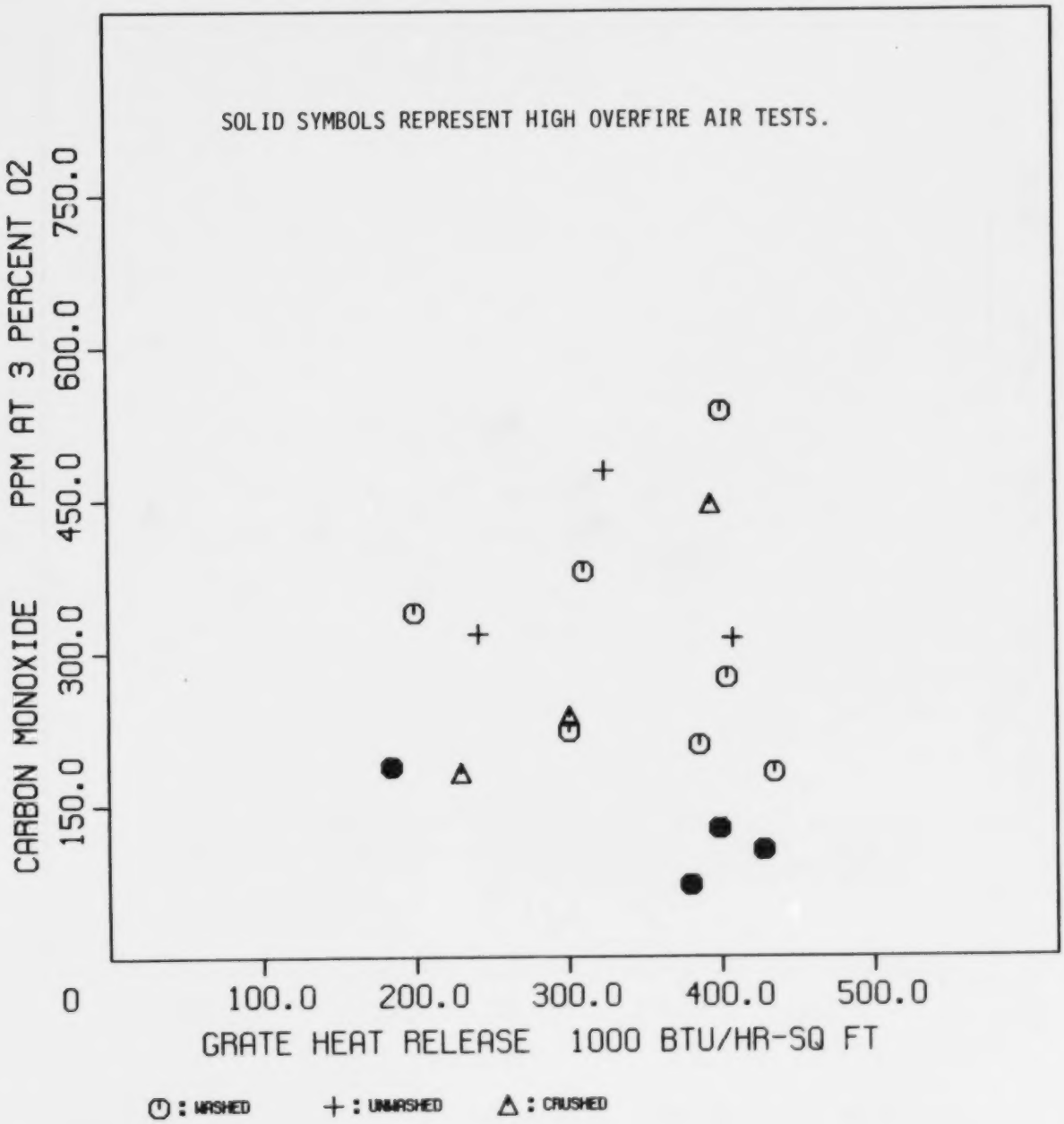

FIG. 5-9

CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE K

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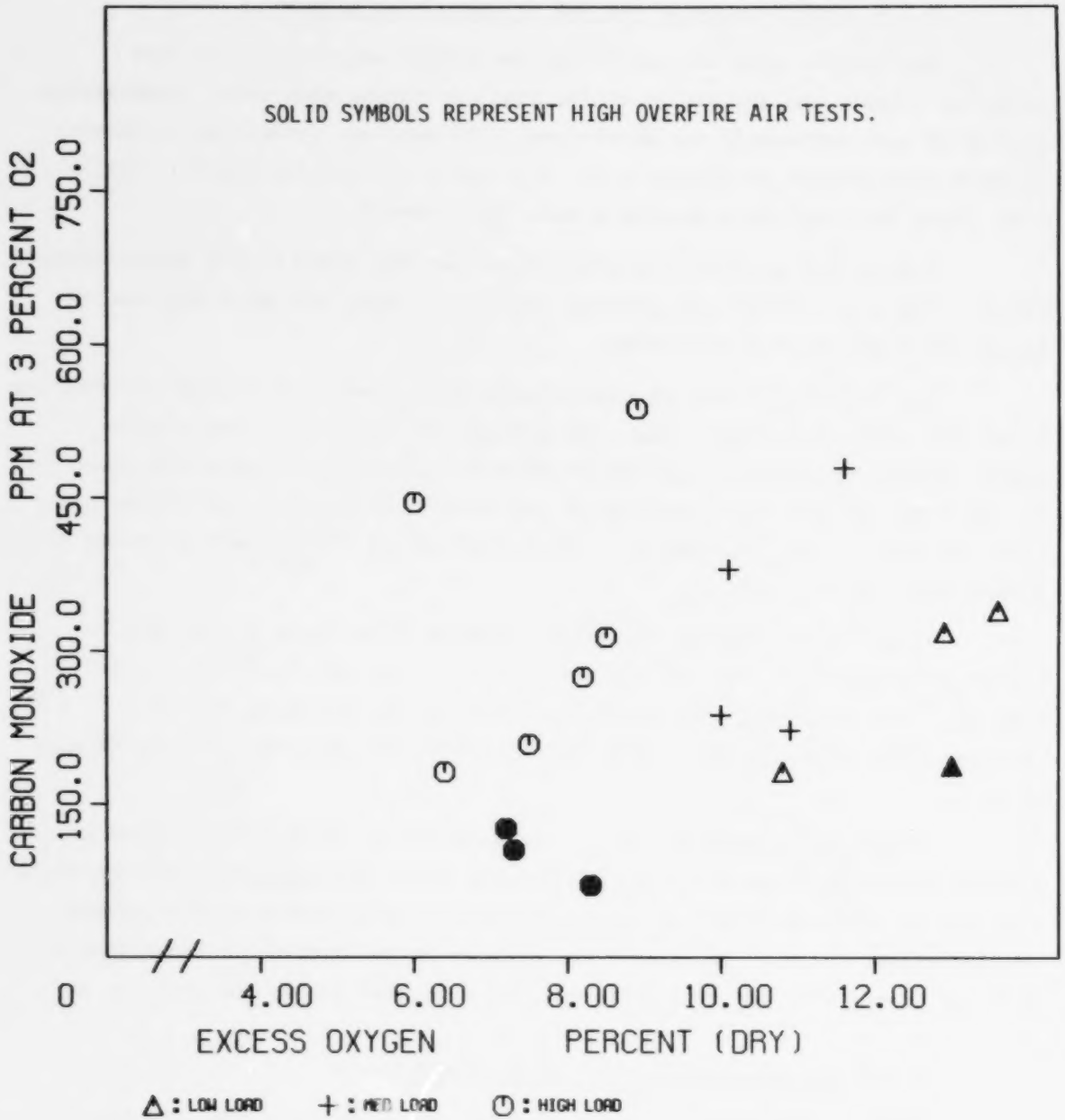

FIG. 5-10
CARBON MONOXIDE VS. EXCESS OXYGEN
TEST SITE K

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5.2.5 Combustibles in the Ash vs Grate Heat Release

Ash samples were collected from the bottom ash hopper, the dust collector hopper, and the boiler outlet flue gas during each test. Combustible content of each ash sample was determined. The data are plotted as a function of grate heat release in Figures 5-11, 5-12 and 5-13, and section 5.7, Table 5-24, lists the complete combustible data for Boiler K.

Figure 5-11 presents the percent combustible found in the boiler outlet flyash. Separate symbols are used for the three coals, and solid symbols indicate the high overfire air tests.

The flyash averaged 32% combustible matter and shows a slight increasing trend with increasing load. Coal type did not correlate with combustible level. Excess oxygen, although not shown here, also did not correlate. Overfire air was the only test variable at this site which changed the flyash combustible level. High overfire air (solid symbols) is seen to have produced the lowest combustible levels.

Figure 5-12 presents the percent combustibles found in the dust collector hopper ash. This ash is the same as the boiler outlet flyash but with the finer particles separated out. Combustibles averaged 29%, were constant with load, and were unaffected by changes in overfire air, excess air, or coal.

Figure 5-13 presents the percent combustible found in the bottom ash. Combustibles range from 21 to 75% and average 42%. This appears to be unusually high for an overfeed traveling grate stoker where combustible levels usually average closer to 20%.[1] Because of the scatter in the data it is impossible to pick out trends with the variables coal, load, excess oxygen and overfire air.

5.2.6 Boiler Efficiency vs Grate Heat Release

Boiler efficiency was determined for each test using the ASME heat loss method. The boiler efficiencies are plotted in Figure 5-14 as a function

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[1]The average is based on data from previous overfeed stokers tested under this contract. Site designation and bottom ash combustible averages were; Site D - 20%; Site H - 16%; Site I - 29%; Site J - 21%.

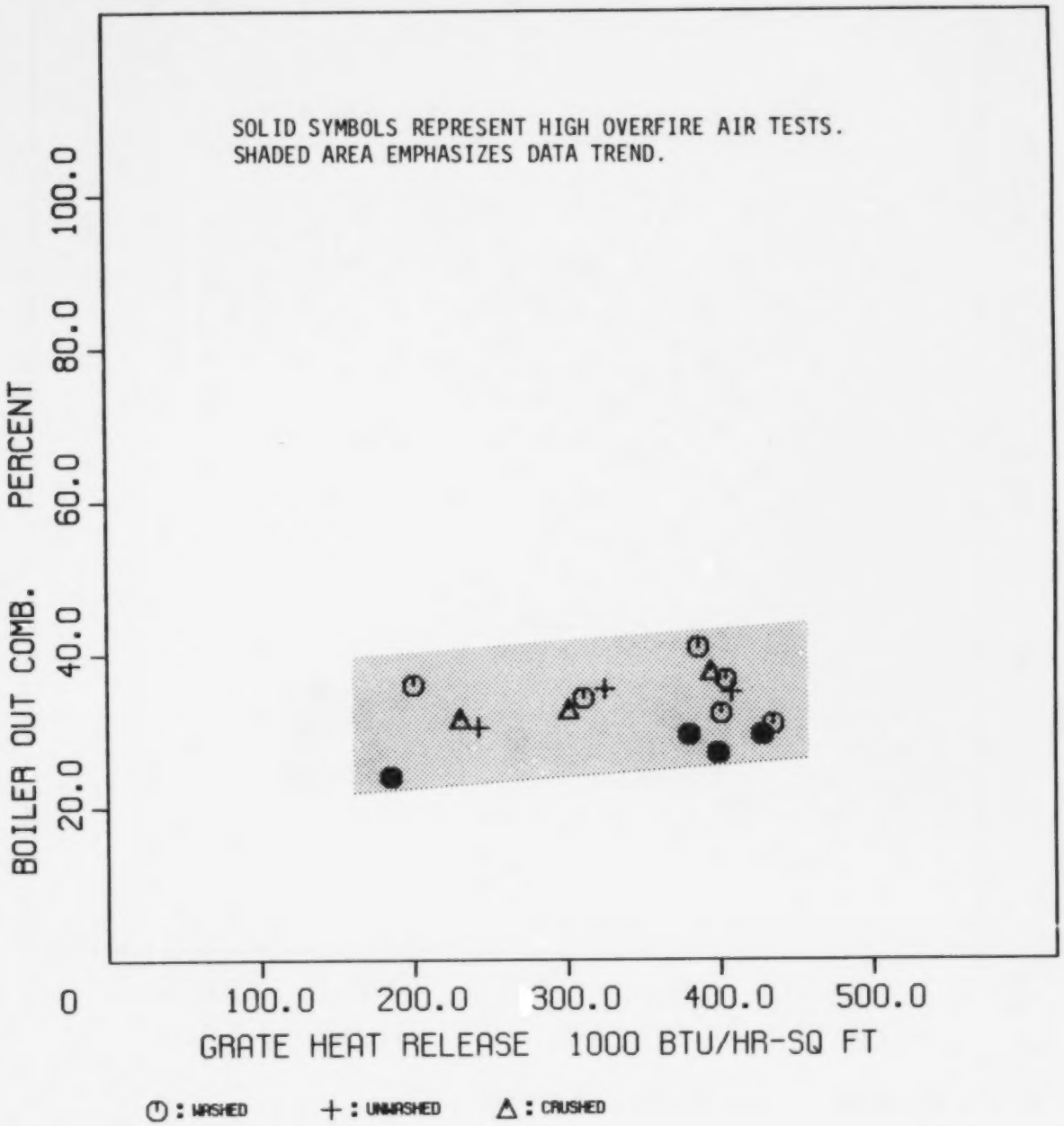

FIG. 5-11
BOILER OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE K

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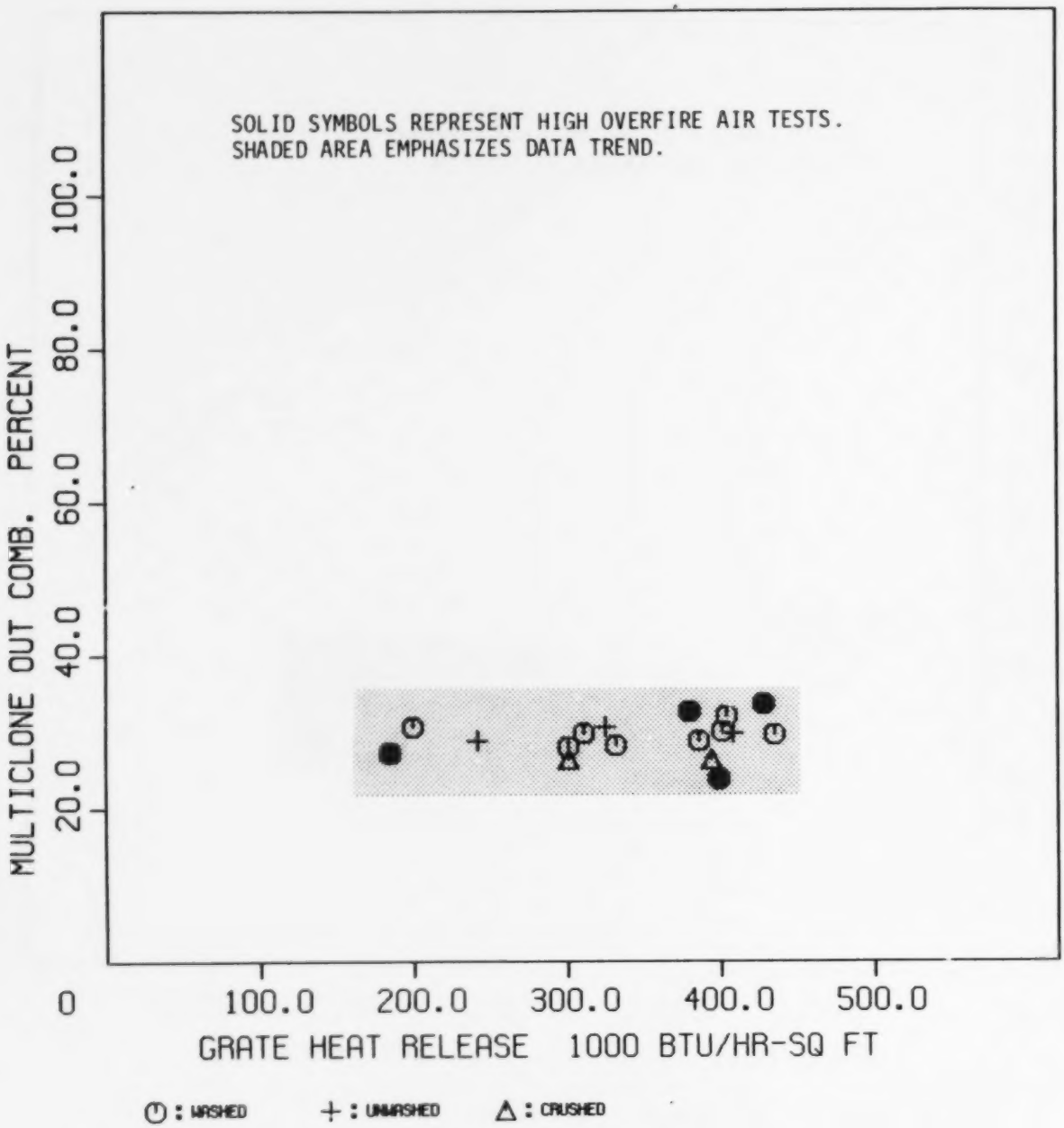

FIG. 5-12
MULTICLONE OUT COMB. VS. GRATE HEAT RELEASE
TEST SITE K

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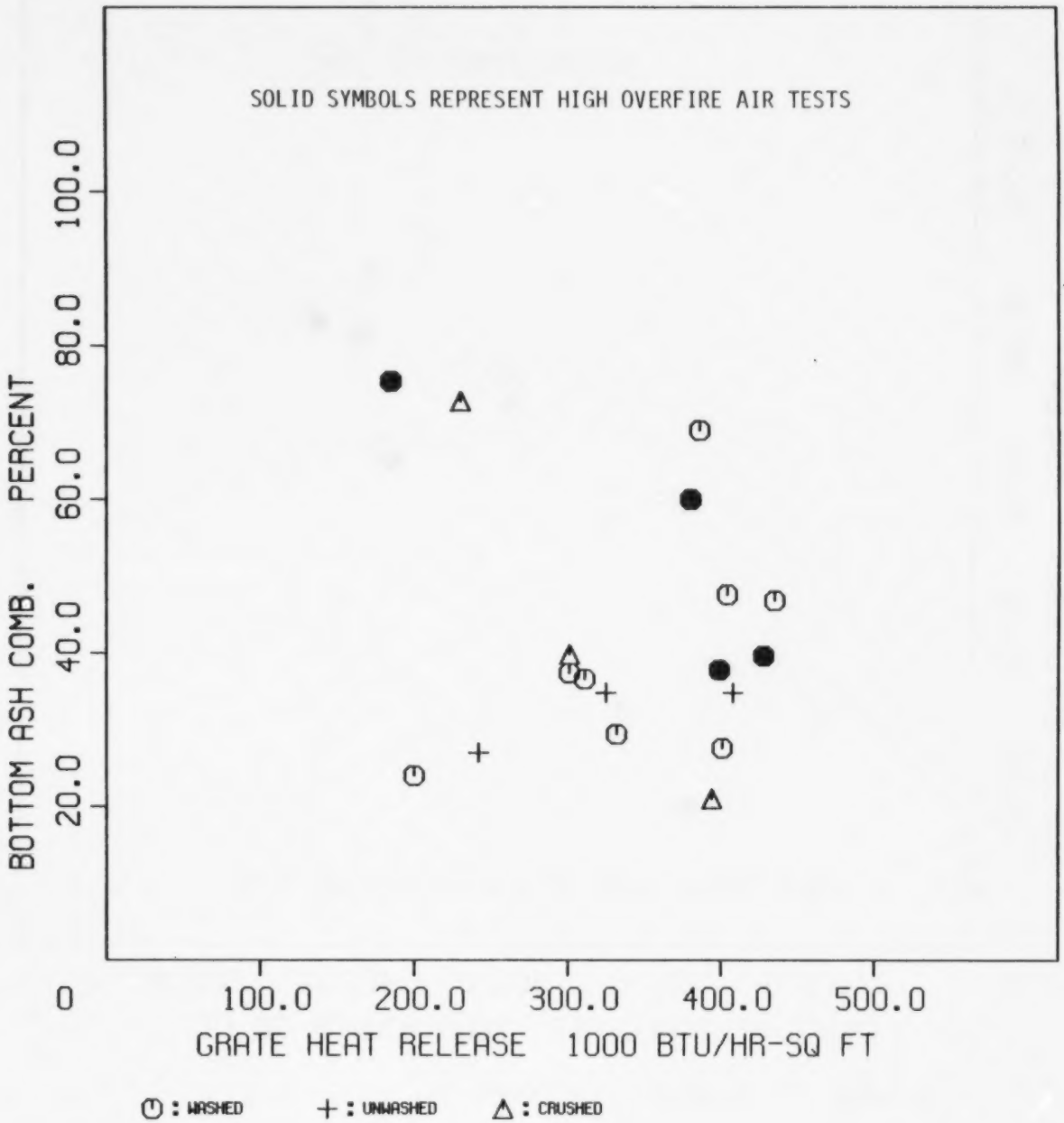

FIG. 5-13

BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

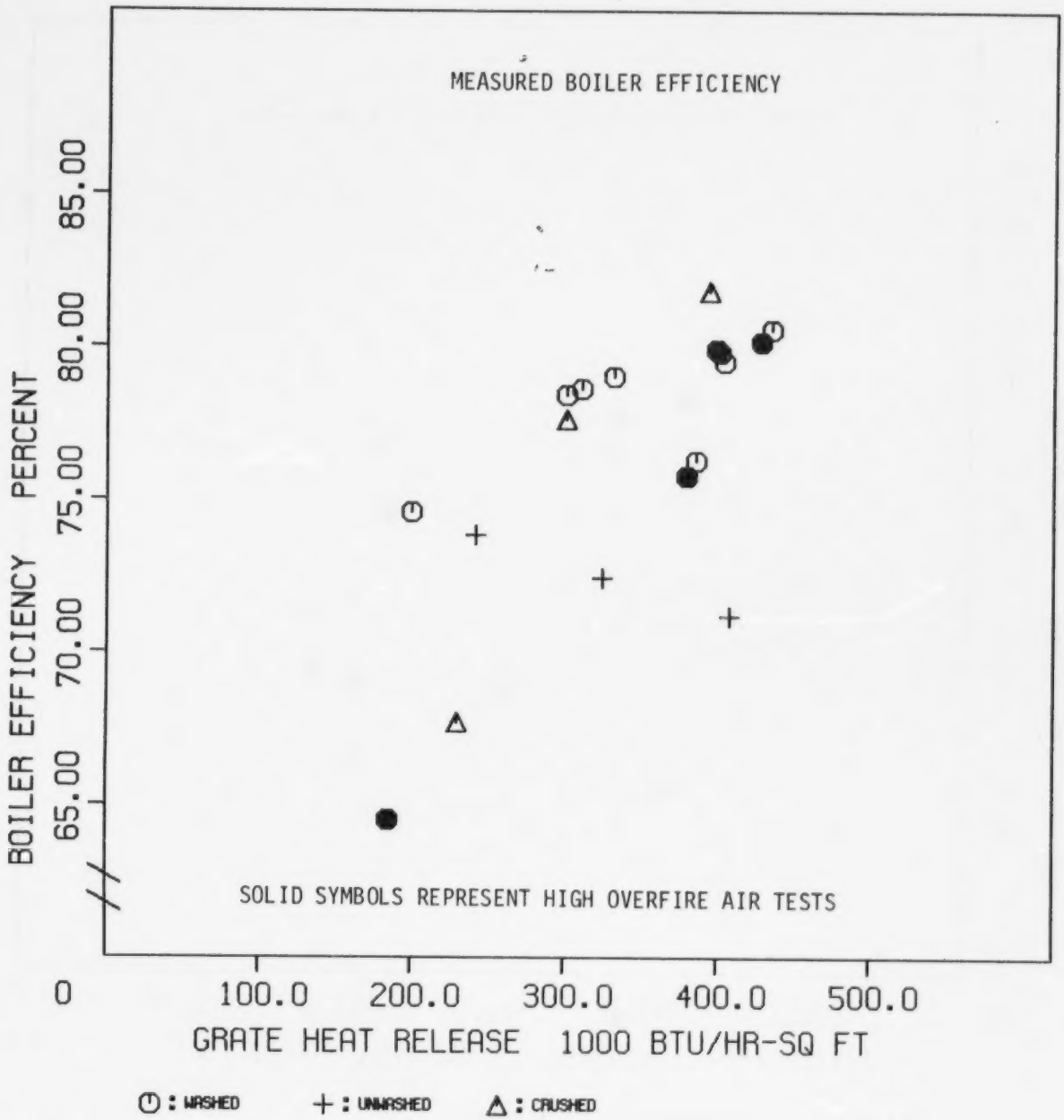

FIG. 5-14

BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

of grate heat release, and a listing of all the heat loss data may be found in Section 5.7, Table 5-23.

The major heat loss factor affecting boiler efficiency at this site was the combustible heat loss, specifically the combustible heat loss in the bottom ash. It has already been mentioned that bottom ash combustible levels were considerably higher at Site K than at previously tested sites with similar equipment. The possibility exists that bottom ash samples were not representative at this site. Therefore, boiler efficiency has also been determined using an assumed 20% combustibles in the bottom ash. These data are presented in Figure 5-15 and in Table 5-7. The reader is advised to use his own judgement in interpreting the bottom ash combustible heat loss.

Table 5-7 presents the average boiler efficiency and heat loss data obtained at Site K for each of the three test loads. Boiler efficiency was greatest at full load where it averaged 78.4% (80.3% if 20% bottom ash combustibles is assumed).

TABLE 5-7

BOILER EFFICIENCY VS LOAD

	AVERAGE HEAT LOSSES, %				
	Dry Gas	Flyash Combustibles	Bottom Ash Combustibles	Other	% BOILER EFFICIENCY
100% Load	10.61	0.48	3.65 (1.69)*	6.80	78.37 (80.33)*
75% Load	12.71	0.52	2.52 (1.45)	7.00	77.25 (78.32)
50% Load	13.68	0.35	8.41 (2.79)	7.40	70.16 (75.78)

* Data in parenthesis are based on 20% combustibles by weight in bottom ash.

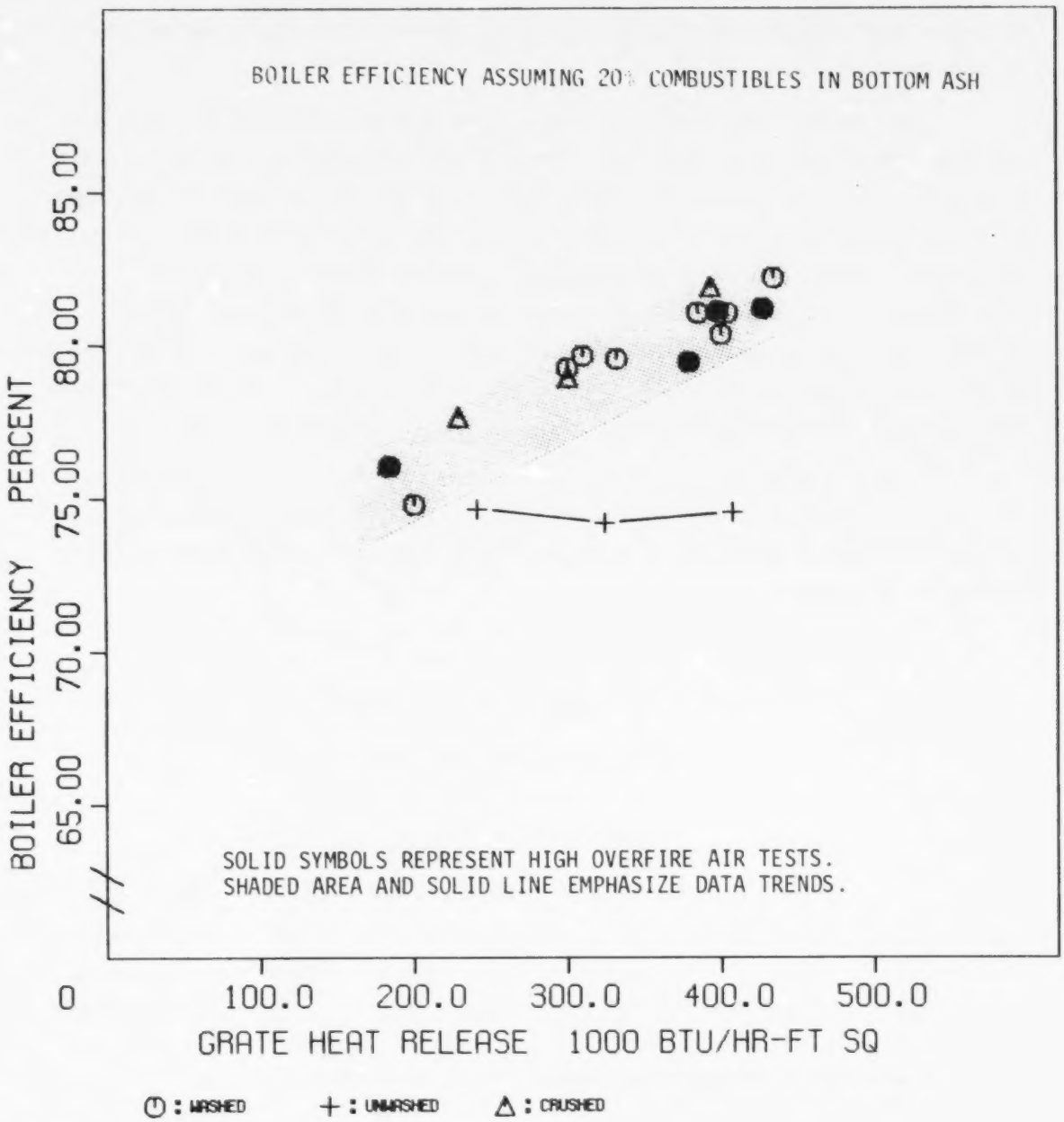

FIG. 5-15

BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE K

4-15900-548

5.3 COAL PROPERTIES

Background information on the three forms of coal tested was given in Section 3.4. This Section will discuss the chemical and physical properties of these coals, and their observed influence on boiler emissions and efficiency.

5.3.1 Chemical Composition of the Coals

Representative coal samples were obtained during each test as described in Section 4.5. A proximate analysis was obtained on each sample. In addition, an ultimate analysis and mineral analysis of the ash were obtained on one sample of each coal for purposes of combustion calculations.

The average proximate analysis for the three coals are compared on a heating value basis in Table 5-8. Such a comparison is often more meaningful than percentage by weight. This comparison shows that the unwashed coal contains more than two and one-half times the ash of the washed coal. This high ash content is the characteristic which differentiates it from the other two coals. The crushed coal differs primarily in its fines, a property discussed in the next subsection. Thus, the three coals each have their distinguishing characteristics.

TABLE 5-8

COAL PROPERTIES CORRECTED TO A CONSTANT 10^6 BTU BASIS

		Washed Coal	Unwashed Coal	Crushed Coal
Moisture,	$lb/10^6Btu$	4.9	5.1	5.7
Ash,	$lb/10^6Btu$	3.1	8.3	3.6
Volatile,	$lb/10^6Btu$	28.4	27.4	28.3
Fixed Carbon,	$lb/10^6Btu$	39.4	40.6	39.4
Sulfur,	$lb/10^6Btu$	0.8	0.8	1.0

The analysis of each coal sample is given in Tables 5-9, 5-10, 5-11, and 5-12.

TABLE 5-9

FUEL ANALYSIS - ALABAMA BRILLIANT COAL (WASHED)
TEST SITE K

TEST NO.	01	02	03	04	05	06	07	08	09	10	11	18	AVG	STD DEV
PROXIMATE (As Rec)														
% Moisture	5.34	7.25	6.45	7.40	6.00	7.13	7.63	7.44	5.99	5.41	6.44	6.80	6.49	0.82
% Ash	5.55	5.17	4.03	3.32	3.44	5.30	4.55	3.45	5.19	4.44	3.51	3.91	4.14	0.78
% Volatile	37.85	39.31	37.58	38.10	38.15	36.20	36.86	36.53	37.04	37.71	37.37	37.42	37.46	0.53
% Fixed Carbon	51.26	48.27	51.94	51.18	52.41	51.37	50.96	52.58	51.78	52.44	52.68	51.87	51.91	0.62
Btu/Lb	13188	12942	13261	13209	13438	12868	13023	13170	13171	13397	13348	13168	13237	125
% Sulfur	1.14	0.29	1.44	1.03	1.03	2.67	0.91	0.86	0.95	1.13	1.21	1.39	1.11	0.19
ULTIMATE (As Rec)														
% Moisture												6.80		
% Carbon												73.85		
% Hydrogen												5.00		
% Nitrogen												1.55		
% Chlorine												0.07		
% Sulfur												1.39		
% Ash												3.91		
% Oxygen (Diff)												7.43		
ASH FUSION (Red)														
Initial Deformation												2100°F		
Soft (H=W)												2280°f		
Soft (H=1/2W)												2310°F		
Fluid												2600°F		
HARDGROVE GRINDABILITY INDEX												40		
FREE SWELLING INDEX												1-1/2		
FOULING INDEX												0.12		
SLAGGING INDEX												0.69		

TABLE 5-10

FUEL ANALYSIS - ALABAMA, BRILLIANT COAL (UNWASHED)
TEST SITE K

TEST NO.	12	13	14	COMP	AVG	STD DEV
PROXIMATE (As Rec)						
% Moisture	5.99	6.59	6.00	4.76	6.19	0.34
% Ash	8.40	8.35	13.96	7.98	10.24	3.22
% Volatile	34.48	33.70	32.88	34.87	33.69	0.80
% Fixed Carbon	51.13	51.36	47.16	52.39	49.88	2.36
Btu/Lb	12601	12468	11770	12768	12280	4.46
% Sulfur	1.19	0.96	0.88	1.10	1.01	0.16
ULTIMATE (As Rec)						
% Moisture				4.76		
% Carbon				72.21		
% Hydrogen				4.68		
% Nitrogen				1.44		
% Chlorine				0.05		
% Sulfur				1.10		
% Ash				7.98		
% Oxygen (Diff)				7.78		
ASH FUSION (Red)						
Initial Deformation				2110°F		
Soft (H=W)				2470		
Soft (H=1/2W)				2510		
Fluid				2700+		
HARDGROVE GRINDABILITY				42		
FREE SWELLING INDEX				--		

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TABLE 5-11

FUEL ANALYSIS - ALABAMA, BRILLIANT COAL (CRUSHED)
TEST SITE K

TEST NO.	15	16	17	COMP	AVG	STD DEV
PROXIMATE (As Rec)						
% Moisture	7.97	6.82	7.27	5.84	7.35	0.58
% Ash	4.57	4.19	5.28	4.15	4.68	0.55
% Volatile	36.85	37.23	36.07	37.53	36.72	0.59
% Fixed Carbon	50.61	51.76	51.38	52.48	51.25	0.59
Btu/Lb	12936	13148	12897	13284	12994	135
% Sulfur	1.13	1.35	1.44	0.94	1.31	0.16
ULTIMATE (As Rec)						
% Moisture				5.84		
% Carbon				74.25		
% Hydrogen				4.97		
% Nitrogen				1.42		
% Chlorine				0.06		
% Sulfur				0.94		
% Ash				4.15		
% Oxygen (Diff)				8.37		
ASH FUSION (As Rec)						
Initial Deformation				2190°F		
Soft (H=W)				2330		
Soft (H=1/2W)				2360		
Fluid				2610		
HARDGROVE GRINDABILITY				40		
FREE SWELLING INDEX				2		

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TABLE 5-12

MINERAL ANALYSIS OF COAL ASH
TEST SITE K

Coal	Alabama Washed	Alabama Unwashed	Alabama Crushed
Mineral Analysis of Ash			
Silica, SiO_2	38.35	52.64	43.86
Alumina, Al_2O_3	26.25	24.64	26.25
Titania, TiO_2	1.14	0.88	1.10
Ferric Oxide, FeO_3	21.19	12.41	15.86
Lime, CaO	5.59	2.62	4.73
Magnesia, MgO	1.57	1.32	1.47
Potassium Oxide, K_2O	1.75	2.75	2.15
Sodium Oxide, Na_2O	0.25	0.27	0.27
Sulfur Trioxide, SO_3	1.99	1.63	3.59
Phos Pentoxide, P_2O_5	0.10	0.05	0.05
Undetermined	1.82	0.79	0.67
Alkalies as Na_2O			
Dry Coal Basis	0.06		
Silica Value	57.50	76.30	66.54
Base: Acid Ratio	0.46	0.25	0.34
T_{250} Temperature	2345°F	2625°F	2490°F
Sulfur Forms			
% Pyritic Sulfur		0.52	0.34
% Sulfate Sulfur		0.03	0.05
% Organic Sulfur		0.55	0.55

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5.3.2 Coal Size Consistency

Coal size consistency was determined for each coal sample obtained at Site K using the procedure described in Section 4.5. The results are listed in Table 5-13, and graphically presented in Figures 5-16, 5-17 and 5-18.

The washed and unwashed coals were observed to be very similar in size consistency with the unwashed coal being only slightly heavier in fines. Both of these coals had a top size of 1-1/4 inches.

The crushed coal consisted of the washed coal run through a 3/4 inch crusher on site. The result was an increase in fines from 20 to 44% passing a 1/4 inch square mesh screen, and a reduction in top size. The crushed coal lies within the ABMA recommended limits of coal sizing for overfeed stokers as shown in Figure 5-18.

5.3.3 Effect of Coal Properties on Emissions and Efficiency

All three coals tested at Site K came from the same mine and were, therefore, nearly identical in chemical composition. However, they differed in ash content and in size consistency. This subsection discusses the impact of these changes on boiler emissions and efficiency. Frequent references are made to figures in Section 5.2, Excess Oxygen and Grate Heat Release, which illustrate the observations.

Excess Oxygen Operating Conditions. The three coals were fired under slightly different excess oxygen conditions. As shown in Figure 5-2, the unwashed coal used more air than the washed coal, and the crushed coal used less air. The differences are slight, on the order of one percent O_2, and will not be considered as variables in this discussion.

Particulate Mass Loading. Coal properties had a major impact on particulate mass loading at this site. As shown in Table 5-14, the high fines crushed coal produced 58% more particulates than the washed coal at full load and the impurity laden unwashed coal produced 180% more particulates. These figures apply only to the uncontrolled, or boiler outlet, particulate mass loading. After the dust collector the particulate mass loadings were quite similar.

TABLE 5-13

AS FIRED COAL SIZE CONSISTENCY
TEST SITE K

	Test No.	PERCENT PASSING SCREEN SIZE 1"	1/2"	1/4"	#8	#16
Alabama Brilliant (Washed)	01	67.9	37.9	21.7	9.4	5.4
	02	85.9	41.6	19.0	3.8	0.4
	03	70.0	35.4	20.2	10.3	5.8
	04	81.9	39.8	21.5	10.2	6.0
	05	73.5	29.8	16.1	8.4	5.1
	06	62.6	28.2	15.6	8.4	5.7
	07	75.3	39.3	21.4	9.7	5.9
	08	75.5	36.9	19.3	9.5	5.8
	09	81.6	49.8	30.9	13.4	7.6
	10	68.9	25.0	14.5	8.1	5.0
	11	72.4	36.9	20.9	9.6	5.9
	18	78.4	40.4	23.2	10.9	6.0
	Average	74.5	36.8	20.4	9.3	5.4
(Unwashed)	12	63.4	36.9	23.1	14.9	11.1
	13	65.4	45.6	32.0	18.9	12.5
	14	57.1	34.2	21.7	13.2	9.0
	Composite	61.0	35.5	22.7	14.0	9.8
	Average	61.7	38.1	24.9	15.3	10.6
(Crushed)	15	96.7	78.6	53.7	25.8	13.8
	16	93.7	72.2	39.4	20.7	13.5
	17	93.2	63.3	39.4	20.0	12.4
	Composite	96.3	67.6	42.4	21.6	13.2
	Average	95.0	70.4	43.7	22.0	13.2

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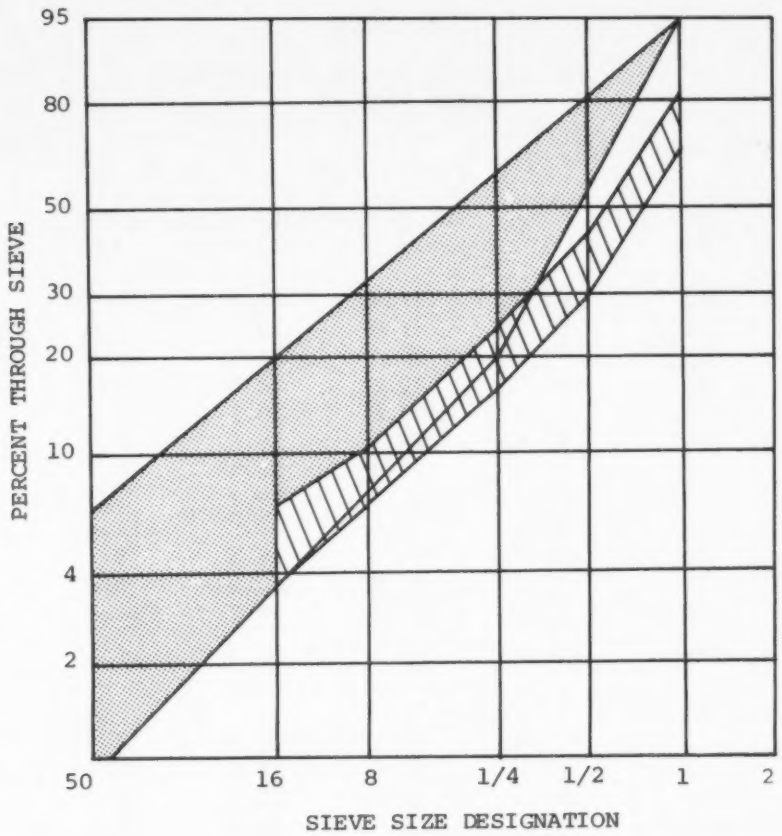

Figure 5-16. Size Consistency of "As Fired" Washed Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site K

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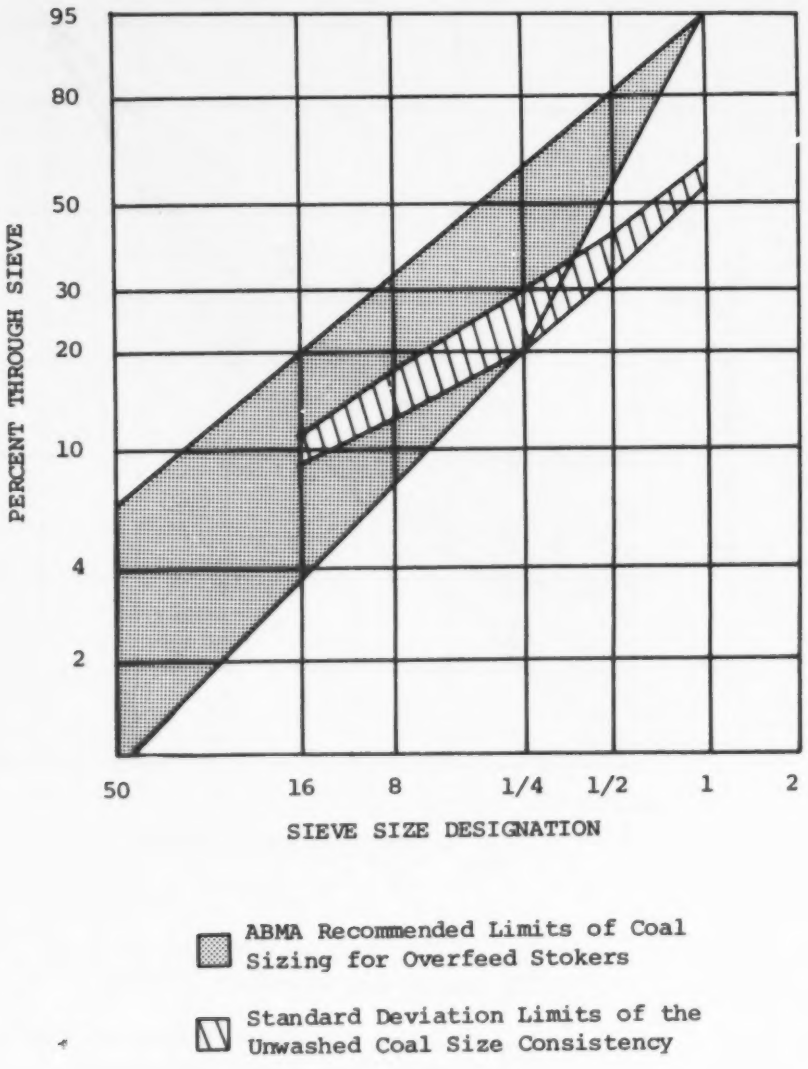

Figure 5-17. Size Consistency of "As Fired" Unwashed Coal vs Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site K

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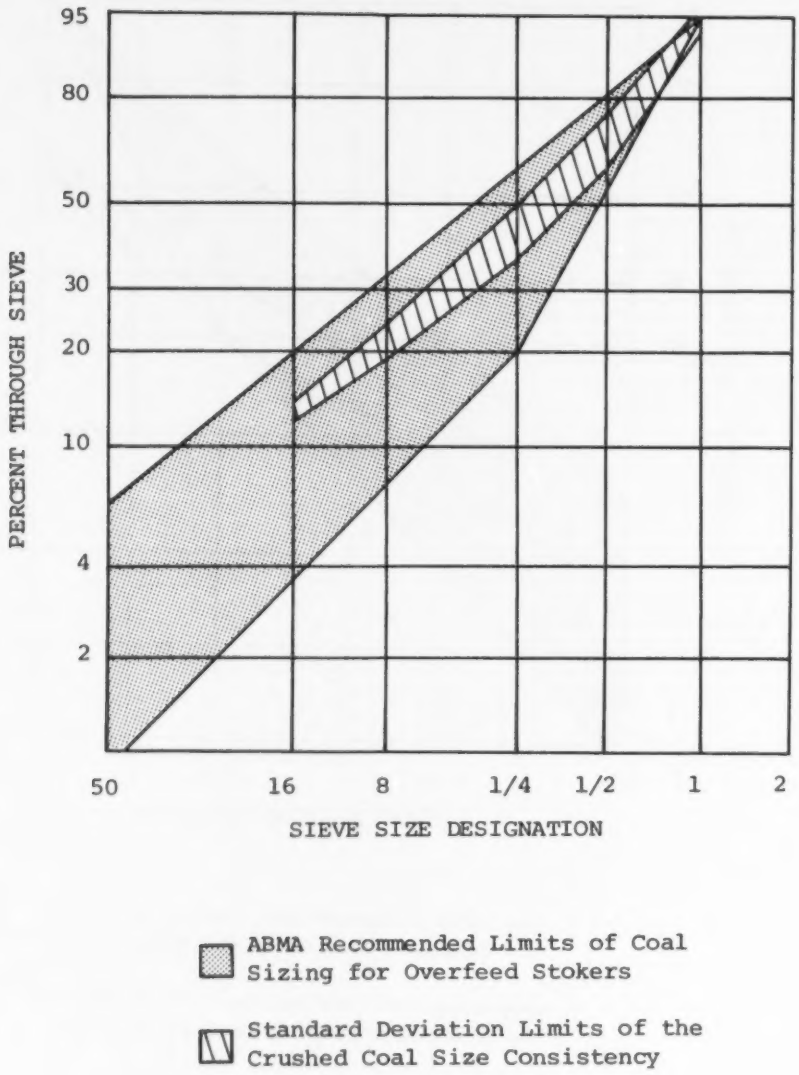

Figure 5-18. Size Consistency of "As Fired" Crushed Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site K.

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TABLE 5-14

PARTICULATE LOADING VS COAL

	Uncontrolled Particulate $lb/10^6Btu$			Controlled Particulate $lb/10^6Btu$		
	50% Load	75% Load	100% Load	50% Load	75% Load	100% Load
Washed Coal	0.61	0.75	0.78	0.17	0.17	0.14
Crushed Coal	0.70	1.13	1.23	0.14	0.15	0.14
Unwashed Coal	1.25	2.06	2.20	0.24	0.20	0.16

The data are graphically presented in Figures 5-3 and 5-4 of Section 5.2.

Nitric Oxide. Nitric oxide concentrations were not altered by the coal changes other than a slight decrease while firing the crushed coal which can be attributed to reduced excess air. The data are graphically presented in Figure 5-7 of Section 5.2.

Carbon Monoxide. Carbon monoxide concentrations were not altered by the coal changes. The data are graphically presented in Figure 5-9 of Section 5.2.

Sulfur Dioxide. Fuel sulfur was not a variable in these tests. However, sulfur dioxide (SO_2) and sulfur trioxide (SO_3) were measured three times during one test on the washed coal. Two measurements were made using the Shell-Emeryville wet chemical method and one measurement was made using the very similar EPA Method 6. The results are presented in Table 5-15 along with measured sulfur concentrations in the bottom ash, flyash and coal. All measurements have been put on a common heat input basis.

TABLE 5-15

SULFUR MEASUREMENTS

	Sulfur Concentrations as lb $SO_2/10^6$Btu		
	Shell (A)	Shell (B)	Method 6
Sulfur in Flue Gas	1.321	1.237	0.919
Sulfur in Flyash	.005	.005	.005
Sulfur in Bottom Ash	.019	.019	.019
Total	1.345	1.261	0.943
Sulfur in Coal	2.111	2.111	2.111
% Undetected Sulfur	36%	40%	55%

The sulfur balance at this site was very poor, with 1/3 to 1/2 of the fuel sulfur going undetected. The discrepancy could just as well be in the determination of fuel sulfur as in the determination of SOx. Nonetheless, sulfur retention in the ash at this site represents between 1.1% and 2.5% of the fuel sulfur, and the remaining 97.5% to 98.9% may be assumed to be emitted as SO_2 and SO_3.

Combustibles in the Ash. Combustible concentrations in the bottom ash, flyash and dust collector hopper ash were similar for all three coals. The data are presented graphically in Figures 5-11, 5-12 and 5-13 of Section 5.2.

Boiler Efficiency. Crushed coal and Washed coal produced similar boiler efficiencies when fired under similar conditions of load and excess oxygen. Unwashed coal produced a lower efficiency than either of the others because of its greater combustible heat loss.

The unwashed coal contained the same percentage of combustibles in its ash as the other two coals. However, because it contained more than twice the ash of the other two, it also had more than twice the combustible heat loss.

Two comparisons of efficiency data obtained under similar firing conditions but different coals are given in Table 5-16. The first set compares Washed coal and Unwashed coal at 100% load and 8.5% O_2. The second set compares Washed coal and Crushed coal at 74% load and 10% O_2. This data supports the above discussion.

Boiler efficiency is graphically presented in Figures 5-14 and 5-15 of section 5.2.

TABLE 5-16

BOILER EFFICIENCY VS COAL

	BOILER HEAT LOSSES, %				
	Dry Gas	Moisture Related	Combus-tible	Other	% BOILER EFFICIENCY
Washed Coal (Test 4)	10.58	4.74	3.03	2.15	79.53
Unwashed Coal (Test 14)	12.69	4.98	9.03	2.11	71.19
Washed Coal (Test 10)	11.95	4.48	2.60	2.34	78.63
Crushed Coal (Test 15)	12.00	4.87	3.15	2.35	77.63

5.4 PARTICLE SIZE DISTRIBUTION OF FLYASH

Four particle size distribution determinations were made on the flyash at Site K. Three of these measurements were made by Brink Cascade Impactor and one by SASS gravimetrics under the test conditions described in Table 5-17. Sampling procedures and test equipment descriptions are given in Section 4.4.

TABLE 5-17

DESCRIPTION OF PARTICLE SIZE DISTRIBUTION
TESTS AT THE BOILER OUTLET
TEST SITE K

Test No.	Coal	% Design Capacity	O_2 %	OFA "H_2O	Particle Size Distribution Methodology
3	Washed	74	10.9	2.2	Brink Cascade Impactor
8	Washed	100	7.3	4.9	Brink Cascade Impactor
16	Crushed	102	6.0	3.8	Brink Cascade Impactor
18	Washed	78	9.8	2.5	SASS Gravimetrics

The test results are presented in Table 5-18 and in Figures 5-19 and 5-20. As illustrated in Figure 5-19, the flyash from combustion of the crushed coal contained a higher percentage of smaller particles than did the flyash from the washed coal. The medium load test produced a higher percentage of particles below 3 micrometers than either of the high load tests.

The SASS gravimetrics results illustrated in Figure 5-20 give a different size distribution than the equivalent Brink test (Test No. 3). The SASS test shows 6% below 3 micrometers vs 27% below 3 micrometers for the Brink test. At one micrometer the two methods are in closer agreement, showing 5% and 7%, respectively, below one micrometer in diameter.

It is likely that differences in measurement methodology account for some of the discrepancies in size distribution. No speculation is made at this time as to which is more accurate. The final project report may include such an evaluation.

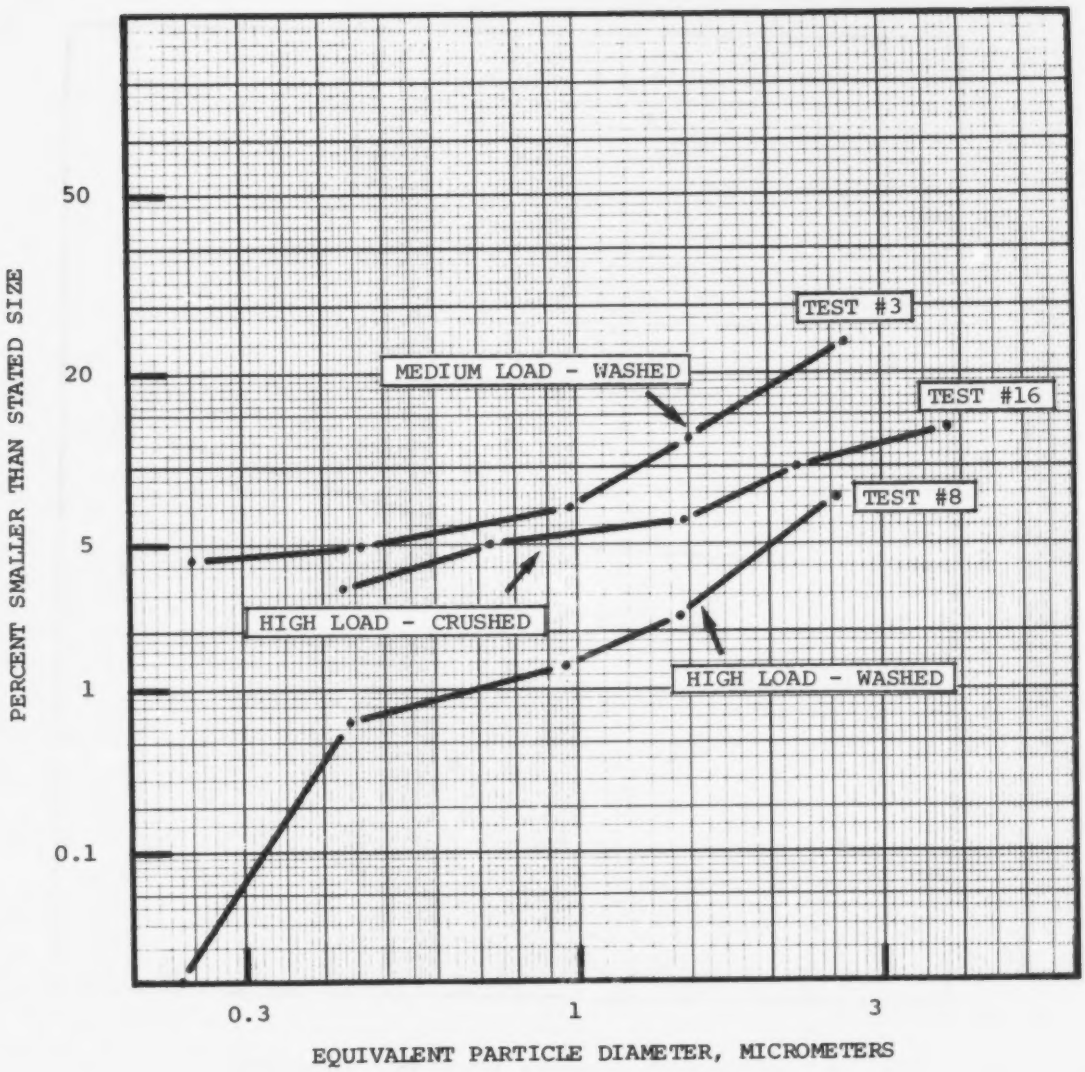

Figure 5-19. Particle Size Distribution at the Boiler Outlet as Determined by Brink Cascade Impactor - Test Site K

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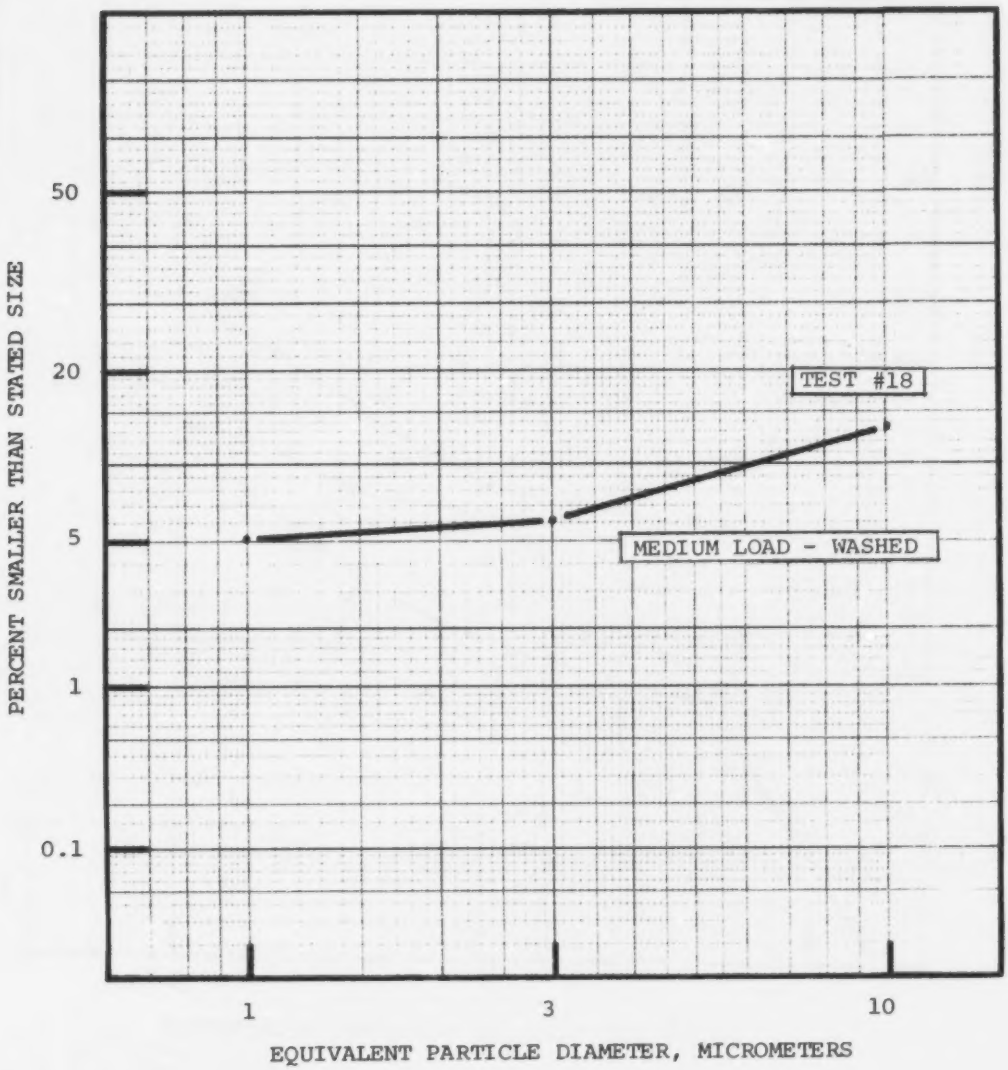

Figure 5-20. Particle Size Distribution at the Boiler Outlet as Determined by SASS Gravimetrics - Test Site K

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TABLE 5-18

RESULTS OF PARTICLE SIZE DISTRIBUTION
TESTS AT THE BOILER OUTLET
TEST SITE K

Test No.	Test Description	Size Distribution % Below 3 μm	Size Distribution % Below 10 μm	Size Concentration lb/10^6Btu Below 3 μm	Size Concentration lb/10^6Btu Below 10 μm
3	Med Load - Washed	27	--	0.216	--
8	High Load - Washed	10	--	0.064	--
16	High Load - Crushed	12	--	0.148	--
18	Med Load - Washed	6	13	0.042	0.092

5.5 EFFICIENCY OF MECHANICAL DUST COLLECTOR

The collection efficiency of the mechanical dust collector was determined in each test by simultaneous particulate mass loading determinations at the collector inlet and outlet. The data are summarized in Table 5-19 and plotted as a function of grate heat release in Figure 5-21.

TABLE 5-19

DUST COLLECTOR EFFICIENCY VS LOAD AND COAL

	50% Load	75% Load	100% Load
Washed Coal	72.0	77.5	81.2
Crushed Coal	79.4	87.0	88.6
Unwashed Coal	80.9	90.4	92.7

The dust collector efficiency was found to be sensitive to the boiler load and to the coal fired. This had a normalizing effect on the stack emissions. As load increased, inlet concentrations increased. But due to increased

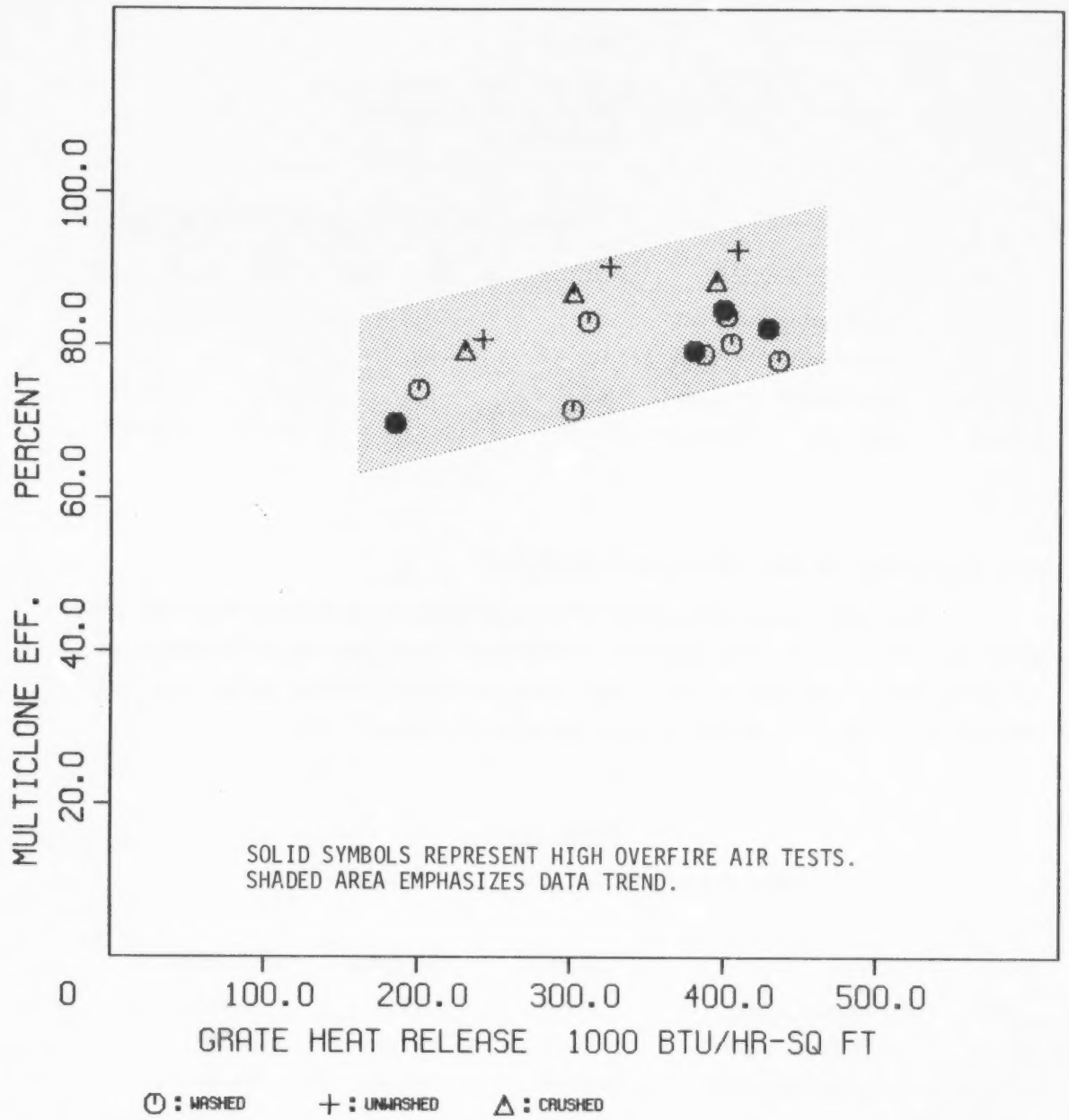

FIG. 5-21

MULTICLONE EFF. VS. GRATE HEAT RELEASE
TEST SITE K

SOLID SYMBOLS REPRESENT HIGH OVERFIRE AIR TESTS. SHADED AREA EMPHASIZES DATA TREND.

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collection efficiency, the outlet concentrations remained relatively constant and in the case of the unwashed coal actually decreased (see Figure 5-4 of Section 5.2.2).

This same normalizing effect was observed with the change in coals. The higher inlet concentrations from the crushed and unwashed coals were reduced more than those of the washed coal.

The complete dust collector efficiency data is listed in Table 5-20.

TABLE 5-20

EFFICIENCY OF DUST COLLECTOR
TEST SITE K

Test No.	Coal Type	Load %	Particulate Loading lb/10^6Btu Collector Inlet	Particulate Loading lb/10^6Btu Collector Outlet	Collector Efficiency %
01	Washed	97	1.240	0.199	84.0
02	Washed	50	0.737	0.190	74.2
03	Washed	71	0.799	0.226	71.7
04	Washed	100	0.758	0.148	80.5
05	Washed	96	0.755	0.158	79.1
06	Washed	95	0.655	0.134	79.5
07	Washed	101	0.850	0.129	84.8
08	Washed	100	0.639	0.112	82.5
09	Washed	41	0.477	0.144	69.8
10	Washed	74	0.707	0.118	83.3
11	Washed	102	0.571	0.124	78.3
				Average	78.9
12	Unwashed	59	1.251	0.239	80.9
13	Unwashed	77	2.060	0.197	90.4
14	Unwashed	101	2.202	0.161	92.7
				Average	88.0
15	Crushed	73	1.127	0.147	87.0
16	Crushed	102	1.231	0.140	88.6
17	Crushed	56	0.698	0.144	79.4
				Average	85.0

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5.6 SOURCE ASSESSMENT SAMPLING SYSTEM (SASS)

One SASS test was run at Test Site K. This test was conducted at 75% of capacity on the Washed coal. SASS test results will not be reported in this report. All SASS test results will be reported under separate cover at the conclusion of this test program. The SASS sample catches will be analyzed by combined gas chromatography/mass spectroscopy for total polynuclear content. In addition, seven specific polynuclear aromatic hydrocarbons (PAH) will be sought. These are listed in Table 5-21.

TABLE 5-21

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE K SASS SAMPLE

Element Name	Molecular Weight	Molecular Formula
7,12 Dimethylbenz (a) anthracene	256	$C_{20}H_{16}$
Dibenz (a, h) anthracene	278	$C_{22}H_{14}$
Benzo (c) phenanthrene	228	$C_{18}H_{12}$
3-methyl cholanthrene	268	$C_{21}H_{16}$
Benzo (a) pyrene	252	$C_{20}H_{12}$
Dibenzo (a,h) pyrene	302	$C_{24}H_{14}$
Dibenzo (a,i) pyrene	302	$C_{24}H_{14}$
Dibenzo (c,g) carbazole	267	$C_{20}H_{13}N$

5.7 DATA TABLES

Tables 5-22 through 5-25 summarize much of the test data obtained at Site K. These tables, in conjunction with Tables 2-1 and 2-2 of the Executive Summary, are included for reference purposes.

TABLE 5-22

PARTICULATE EMISSIONS
TEST SITE K

	Test No.	Coal	Load %	O_2 %	PARTICULATE EMISSIONS lb/10^6Btu	gr/SCF	lb/hr	Velocity ft/sec
BOILER OUTLET	01	Washed	97	8.8	1.240	0.517	79.6	26.45
	02	Washed	50	13.6	0.737	0.185	24.2	20.23
	03	Washed	71	10.9	0.799	0.277	38.5	21.33
	04	Washed	100	8.2	0.758	0.332	49.1	24.88
	05	Washed	96	7.5	0.755	0.355	46.7	25.23
	06	Washed	95	8.3	0.655	0.283	40.8	27.04
	07	Washed	101	7.2	0.850	0.396	54.2	27.02
	08	Washed	100	7.3	0.639	0.299	43.8	25.55
	09	Washed	41	13.0	0.477	0.130	14.1	17.48
	10	Washed	74	10.1	0.707	0.267	35.2	24.70
	11	Washed	102	6.4	0.571	0.288	39.7	25.83
	12	Unwashed	59	12.9	1.251	0.340	48.5	26.60
	13	Unwashed	77	11.6	2.060	0.644	107.0	27.79
	14	Unwashed	101	8.5	2.202	0.939	143.9	31.39
	15	Crushed	73	10.0	1.127	0.415	68.3	24.90
	16	Crushed	102	6.0	1.231	0.628	77.7	25.95
	17	Crushed	56	10.8	0.698	0.237	19.7	20.55
DUST COLLECTOR OUTLET	01	Washed	97	8.7	0.199	0.084	12.8	52.48
	02	Washed	50	13.8	0.190	0.047	6.2	39.59
	03	Washed	71	11.0	0.226	0.078	10.9	41.82
	04	Washed	100	8.1	0.148	0.066	9.6	51.03
	05	Washed	96	8.8	0.158	0.067	9.8	48.79
	06	Washed	95	9.3	0.134	0.053	8.3	51.77
	07	Washed	101	8.1	0.129	0.056	8.2	52.80
	08	Washed	100	7.8	0.112	0.050	7.7	51.34
	09	Washed	41	13.2	0.144	0.038	4.3	32.89
	10	Washed	74	10.2	0.118	0.044	5.9	48.78
	11	Washed	102	7.4	0.124	0.059	8.6	49.56
	12	Unwashed	59	13.6	0.239	0.059	9.3	50.11
	13	Unwashed	77	11.6	0.197	0.062	10.2	53.70
	14	Unwashed	101	8.7	0.161	0.068	10.5	54.46
	15	Crushed	73	10.1	0.147	0.054	8.9	44.95
	16	Crushed	102	6.4	0.140	0.070	8.8	47.05
	17	Crushed	56	11.3	0.144	0.046	4.1	36.59

TABLE 5-23

HEAT LOSSES AND EFFICIENCIES
TEST SITE K

	TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	BOILER EFFICIENCY
ALABAMA BRILLIANT, WASHED	01	11.01	0.49	4.10	0.57	1.83	2.40	0.64	1.50	20.14	79.86
	02	16.37	0.63	4.14	0.39	1.14	1.53	1.22	1.50	25.39	74.61
	03	12.09	0.58	4.02	0.37	2.13	2.50	0.86	1.50	21.55	78.45
	04	10.58	0.67	4.07	0.40	2.63	3.03	0.65	1.50	20.47	79.53
	05	9.82	0.54	4.04	0.44	6.72	7.16	0.65	1.50	23.71	76.29
	06	11.41	0.64	4.23	0.28	5.48	5.76	0.65	1.50	24.19	75.81
	07	10.23	0.71	4.17	0.33	2.49	2.82	0.62	1.50	20.05	79.95
	08	10.55	0.69	4.15	0.27	2.02	2.29	0.62	1.50	19.80	80.20
	09	12.07	0.54	4.04	0.16	15.70	15.86	1.50	1.50	35.51	64.49
	10	11.95	0.48	4.00	0.34	2.26	2.60	0.84	1.50	21.37	78.63
	11	9.59	0.58	4.05	0.25	2.80	3.05	0.61	1.50	19.38	80.62
	18	12.12	0.62	4.10	0.32	1.49	1.81	0.79	1.50	20.94	79.06
UNWASHED	12	15.42	0.57	4.01	0.54	3.06	3.60	1.04	1.50	26.14	73.86
	13	15.38	0.64	4.09	1.04	4.08	5.12	0.80	1.50	27.53	72.47
	14	12.69	0.62	4.36	1.10	7.93	9.03	0.61	1.50	28.81	71.19
CRUSHED	15	12.00	0.74	4.13	0.53	2.62	3.15	0.85	1.50	22.37	77.63
	16	9.60	0.64	4.21	0.66	0.92	1.58	0.61	1.50	18.14	81.86
	17	10.87	0.67	4.13	0.31	13.74	14.05	1.10	1.50	32.32	67.68

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TABLE 5-24

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE K

	Test No.	Boiler Outlet	Dust Collector Hopper	Bottom Ash
Alabama Brilliant, Washed	01	32.2	30.08	27.63
	02	36.0	30.68	23.93
	03		27.99	37.50
	04	36.7	32.08	47.59
	05	40.8	28.77	69.07
	06	29.4	32.60	60.00
	07	27.0	23.75	37.85
	08	29.4	33.56	39.52
	09	24.0	27.22	75.48
	10	34.2	29.76	36.57
	11	30.9	29.62	46.78
	18	----	28.12	29.50
	AVG	32.1	29.52	44.29
Unwashed	12	30.4	28.90	27.02
	13	35.5	30.64	34.78
	14	35.1	29.72	34.78
	AVG	32.1	29.75	32.19
Crushed	15	32.8	26.49	39.84
	16	37.8	26.46	21.00
	17	31.6	--	72.72
	AVG	34.1	26.48	44.52

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TABLE 5-25

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE K

Test No.	Capacity %	Steam Flow lb/hr	Heat Input* 10^6Btu/hr	Heat Output** 10^6Btu/hr	Front Foot Heat Release 10^6Btu/hr-ft	Grate Heat Release 10^3Btu/hr-ft^2	Furnace Heat Release 10^3Btu/hr-ft^3
1	97	48,708	64.2	58.0	6.42	401	24.6
2	50	24,968	32.1	29.7	3.21	201	12.3
3	74	35,593	48.1	42.3	4.81	301	18.4
4	100	49,750	64.7	59.2	6.47	405	24.8
5	96	47,750	61.8	56.8	6.18	386	23.7
6	95	47,454	60.5	56.5	6.05	380	23.1
7	101	50,250	63.8	59.8	6.38	399	24.4
8	100	50,000	68.5	59.5	6.85	428	26.2
9	41	20,250	29.6	24.1	2.96	185	11.3
10	74	36,782	49.8	43.7	4.98	311	19.1
11	102	51,102	69.6	60.8	6.96	435	26.6
12	59	29,357	38.8	34.9	3.88	242	14.8
13	77	38,250	51.9	45.5	5.19	325	19.9
14	101	50,602	65.3	60.2	6.54	408	25.0
15	73	36,316	48.1	43.2	4.81	301	18.4
16	102	50,800	63.1	60.5	6.31	394	24.1
17	56	27,750	36.8	33.0	3.68	230	14.1
18	78	39,000	53.2	46.4	5.32	333	20.4

* Heat Input Data Based on Coal Flow Rate and Heating Value

** Heat Output Data Based on Steam Flow Rate and Enthalpy of steam and feedwater

APPENDICES

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6$BTU	ng/J	430
g/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	2324
BTU/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
BTU/ft/hr	W/m	0.9609
BTU/ft/hr	J/hr/m	3459
$BTU/ft^2/hr$	W/m^2	3.152
$BTU/ft^2/hr$	$J/hr/m^2$	11349
$BTU/ft^3/hr$	W/m^3	10.34
$BTU/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

FOR TYPICAL COAL FUEL

ppm @ 3% O_2 (SO_2)	ng/J	($lb/10^6$Btu)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (SO_3)	ng/J	($lb/10^6$Btu)	1.063 ($2.47x10^{-3}$)
ppm @ 3% O_2 (NO)*	ng/J	($lb/10^6$Btu)	0.399 ($9.28x10^{-4}$)
ppm @ 3% O_2 (NO_2)	ng/J	($lb/10^6$Btu)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J	($lb/10^6$Btu)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J	($lb/10^6$Btu)	0.213 ($4.95x10^{-4}$)
g/kg of fuel**			

*Federal environmental regulations express NOx in terms of NO_2; thus NO units should be converted using the NO_2 conversion factor.

**Based on higher heating value of 10,000 Btu/lb. For a heating value other than 10,000 Btu/lb, multiply the conversion factor by 10,000/(Btu/lb).

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APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6BTU$	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	0.000430
J/hr/m	BTU/ft/hr	0.000289
$J/hr/m^2$	$BTU/ft^2/hr$	0.0000881
$J/hr/m^3$	$BTU/ft^3/hr$	0.0000269
W	BTU/hr	3.414
W	J/hr	0.000278
W/m	BTU/ft/hr	1.041
W/m^2	$BTU/ft^2/hr$	0.317
W/m^3	$BTU/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

FOR TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SO_2)	1.18
ng/J	ppm @ 3% O_2 (SO_3)	0.941
ng/J	ppm @ 3% O_2 (NO)	2.51
ng/J	ppm @ 3% O_2 (NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69
ng/J	g/kg of fuel	0.000233

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APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By	% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF. (Dry @ 12% CO_2)	
	S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel — S	1		0.666		0.370		13.2×10^{-4}		1.48	
% Weight In Fuel — N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu — SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
lbs/10^6Btu — NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal — SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
grams/10^6Cal — NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2) — SOx	758		505		281		1		1127	
PPM (Dry @ 3% O_2) — NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2) — SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
Grains/SCF (Dry @ 12% CO_2) — NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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16. ABSTRACT The report gives results of field measurements made on a 50,000 lb steam/hr coal-fired overfeed stoker with traveling grate. The effects of various parameters on boiler emissions and efficiency were studied. Parameters include overfire air, excess oxygen, grate heat release, and coal properties. Measurements include O2, CO2, CO, NO, SO2, SO3, incontrolled particulate loading, particle size distribution of the uncontrolled flyash, and combustible content of the ash. In addition to test results and observations, the report describes the facility tested, coals fired, test equipment, and procedures. On the primary coal, full-load uncontrolled particulate loading on this unit averaged 0.78 lb/million Btu, while full-load controlled particulate loading averaged 0.14 lb/million Btu. Full-load NO emissions averaged 0.31 lb/million Btu.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Improvement	Air Pollution Control	13B	14G
Boilers	Efficiency	Stationary Sources	13A	
Combustion	Flue Gases	Combustion Modification	21B	
Coal	Fly Ash	Spreader Stokers	21D	
Field Tests	Particle Size	Traveling Grate Stokers	14B	
Dust	Nitrogen Oxides	Particulate	11G	07B
Stokers	Sulfur Oxides	Overfire Air		

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